

***BENEATH THE BOTTOM LINE: AGRICULTURAL APPROACHES TO REDUCE
AGRICHEMICAL CONTAMINATION OF GROUNDWATER***

Volume II--Contract Papers

Part D: Pest and Pesticide Management

1. Improving Pesticide Management Practices -- Franklin R. Hall
2. Integrated Pest Management: Potential for Reducing Agrichemical Contamination of Groundwater -- Frank G. Zalom, Michael W. Stimmann, Janet M. Smilanick
3. Irrigation/Chemigation: Implications for Agrichemical Contamination of Groundwater -- E. Dale Threadgill
4. Agrichemical Application Technology: Potentials To Reduce Groundwater Contamination -- Maurice R. Gebhardt

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IMPROVING PESTICIDE MANAGEMENT PRACTICES

by

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IMPROVING PESTICIDE MANAGEMENT PRACTICES

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I. INTRODUCTION

Pesticides and Application Technology

Pesticides are applied in agricultural systems for the purpose of protecting plants from injury by insects, disease, etc., which today still destroy almost 33% of all food crops. Applications are considered effective if they achieve the desired biological results, and economic if there is a crop yield and quality response above and beyond the cost of chemicals and their application. Yet the use of pesticides has also resulted in significant costs to public health and the environment [Pimentel & Levitan, 1986]. In general, the amount of pesticides released into the environment has risen ca. 1900% in the 50-year period between 1930 and 1980 [Hess, 1987]. The improved efficacy of the more recent pesticides has allowed doses to be reduced in some instances to a few grams per hectare (Figure 1). However, the capability to deliver these reduced amounts of agrochemicals remains suspect and numerous researchers have estimated that only "1-2%

arrive at the target" [Hall, 1985]. Thus it is clear that because of this poor efficiency of utilization, application or dose transfer technology has been unduly neglected and suggests that any further improvement in intrinsic activity of pesticides may in fact be off-set by inefficiencies in delivery mechanisms.

Procopcy [86] asks, "Why the rapid increase in the use of pesticides throughout the world, in spite of the continuing evidence of pest resistance, groundwater contamination, worker exposure, and pests continuing to remain as "pests"?" Procopcy concludes that this dilemma is due to the following factors:

- (1) Vastly changing agricultural practices.
- (2) Especially in the US, an increase in a "pest-free" environment and food (pestophobia), e.g., the drive for even better cosmetic appearances for an affluent buying public.
- (3) An increasingly mobile society (and with human transport comes pest transport).
- (4) Development of pest resistance to pesticides.
- (5) The inability of applied entomologists to take a leadership role in problem solving on a wider scale vs. the short term, less integrated approaches, and
- (6) Lack of selectivity of current molecules (due to limited market potentials) which is now being made increasingly difficult because of pressures to create greater regulatory constraints on pesticide usage.

These very factors also contribute to the problem of how to improve the pesticide delivery process at the farm level where the demand for greater

production (and quality) continues to provide incentives (profit) for the use of pesticides. Thus, pesticides which are currently used at a rate approaching one billion pounds per year in the United States are expected to continue to play a major role for the foreseeable future in crop protection scenarios for most crop systems [Hall, 1985].

Although the application rate of insecticides has steadily declined from 5-6 kg/ha (with carbaryl) to as low as 20 gm/ha with the introduction of the new synthetic pyrethroids (Figure 1), these increasingly lower rates of chemical per hectare or per volume of coverage mandate the need for additional application precision. However, the relationships between the spray process, the target pests and crop canopies are many, complex, and not well understood. Targeting the application of a toxicant to a more accurately defined site will improve cost effectiveness, subject nontarget sites to less chemical exposure, prevent product wastage and reduce environmental concerns.

The advancement of reduced or no-tillage cultural systems requires new concepts of fertilizer and chemical placement. Fertilizer application equipment technology research is very limited in both the public and private sector. Yet by the year 2000 it is estimated that 70 percent of the tillable land in the United States will be in some form of conservation tillage management. This will require significant changes in application techniques and must trigger development of new equipment. Multiple systems for seeding or planting must be carefully and scientifically coordinated to accommodate one-trip farming.

While vastly improved agrochemicals are available for use in the 1980's, neither the development of efficient delivery systems nor the development

of a basic understanding of the complex aspects of agrochemical application technology have kept pace with these advancements and public concerns. This deficiency was emphasized by the fact that those attending the ARI, 1985 Conference, primarily biologists and engineers, were meeting in a group forum for the first time in the United States. If the U.S. is to meet the challenge of providing an adequate supply of safe food and fiber in the 21st century with the use of agrochemicals and fertilizers, we must develop the means to apply them efficiently while at the same time protecting the environment. Clearly, any improvement in application technology will depend upon more intensive, systematic, integrated and basic studies of physical, meteorological and physicochemical parameters that control the behavior of agrochemicals and their use [Hall, 1985].

Groundwater

The dependence of the U.S. upon groundwater is substantial. Approximately 86 percent of the total water resource in the contiguous United States is found in underground aquifers. Groundwater supplies about 24 percent of the nation's freshwater and its use is increasing about 4 percent annually. Of the total water withdrawn, 68 percent is used for irrigated agriculture. Half the U.S. population depends upon wells for drinking water, with 95 percent of rural households depending solely upon groundwater. Of additional importance, about 30 percent of the nation's stream flow is supplied by groundwater seepage [Scott, 1985].

The nation's groundwaters are being adversely affected by man's activities, including intrusion into groundwater of agricultural chemicals applied to soil and crops. Even with significant increases in monitoring, the extent of groundwater contamination will not be adequately assessed in

the near future, nor will be the relative impact of agricultural and other sources of chemicals. In addition, institutional arrangements for groundwater allocation and protection are in their infancy. Substantial efforts must be organized to ensure the future of our groundwater supplies [Scott, 1985].

Contamination or depletion of groundwater is a crucial concern throughout the nation. Contamination may persist for many years because groundwater moves very slowly and biologically or chemically active zones that can degrade contaminants are scarce. Thus, prevention is a critical public objective because contamination is so irreversible. In addition, water is in constant movement (Figure 2) throughout the environment and thus the interactions are complex.

Advances in analytical chemistry now allow detection of chemicals in groundwater at very low concentrations. Because the toxicological effects of many of these chemicals have not been clearly established, public concern is understandably great. Thus, demands have been made for more regulation of agricultural, industrial and municipal activities that introduce chemicals to groundwater. Federal, state and local programs have been affected, but it is uncertain whether we are even moving in the best direction. This increased regulation can add economic burdens, revocation of pesticide registrations and substantial changes in land use. Few non-regulatory measures have been attempted. Whether these actions will protect our groundwater from further damage will not be clear until (1) we better understand the physical, chemical and biological complexities of the soil filter that overlies our groundwater and (2) we systematically review institutional responses to these problems. Society has a tremendous stake

in preventing groundwater contamination. Chemicals are indispensable in modern agriculture, but some can impair the use of groundwater for crop or animal production, or for domestic water supply. Other sources of groundwater contamination are not from agriculture, as in many urban areas or in locations that have been used for waste disposal. The relative importance and contribution of each of these various sources of contamination needs closer examination [CAST, 1985]. Public concerns arising from isolated contamination events may eventually cause severe (and possibly unjustified) constraints on use of a wide range of chemicals. In the interest of maintaining high agricultural productivity, it is essential to develop procedures to prevent groundwater contamination rather than reacting to contamination after it occurs.

The specific practice that causes groundwater contamination varies by geographical region. Typical groundwater contaminants are inorganic salts, pesticides, nitrates, seawater, gasoline, or organic wastes. The nature and intensity of the physical, chemical and biological processes that affect the fate of these chemicals vary by region. The social, economic and political implications of contaminated or insufficient groundwater also vary according to locale [CAST, 1985].

The Extent of The Contamination and The Interaction

Within the last ten years, cases of groundwater contamination have been reported throughout the United States, and some now estimate that up to 2% of the total groundwater volume in the U.S. is severely polluted, including sole source aquifers and the supplies of densely populated areas (Josephson, 1982). Hundreds of wells in nearly every state have been contaminated by synthetic organic chemicals, several of which are confirmed human or animal

carcinogens [Burmaster and Harris, 1982]. A groundwater quality survey conducted by the U.S. EPA in 1982 discovered that approximately 28% of the larger public water systems in this country (those serving more than 10,000 people) and about 17% of the smaller systems (those serving fewer than 10,000 people) showed detectable levels of synthetic chemicals [Bacon and Olecko, 1985]. Once again, "detection" does not necessarily mean a hazard. In 1985, there had been no formal survey conducted on the millions of residential wells across the country, which serve an estimated 40 million Americans. However, EPA has just proposed a groundwater strategy [EPA, 1987] for addressing the contamination [by agricultural chemicals]. The US Geological Survey and EPA are each also completing well water surveys [USGS, 1988].

"In retrospect, it is obvious that we have forgotten a fundamental ecological principle, that everything is connected to everything else" [Bacon and Olecko, 1985]. The materials deposited in one area of the environment often end up in another segment, sometimes with consequences as severe as the original problem. Thus, the improvement of air and surface water quality have increased the amount of toxic wastes discharged to the land. These wastes are now recognized as a major contributor to the problem of groundwater contamination.

Of principal concern is the downward movement of pesticides in water through soils, and the occurrence and significance of pesticide residues in groundwater. The potential for loss of pesticides to groundwater exists wherever pesticides are used, but the extent varies with the chemical nature of the pesticide and the soil as well as with other circumstances. Bacon and Olecko [1985] summarize groundwater contamination by placing it into two

categories: (1) waste disposal sources and (2) non-waste disposal sources [Table 1] which allows the reader to see the myriad of sources and the discussion gives insight into the complexity of this issue.

The loss of pesticides from soil to groundwater is determined by innumerable factors and conditions, which for convenience are classified according to their influence on four processes: volatilization (with subsequent loss to the atmosphere), decomposition, retention by the soil, and transport by water. The first two processes reduce the total amounts of pesticides available for downward movement, and the third decreases the availability of the existing amounts for downward movement, and the fourth has to do with the adequacy of the processes capable of causing movement. In addition, small quantities of pesticides are removed from the land in agricultural products.

Table 2 summarizes the behavior of pesticides in terms of these four processes in five zones of the environment, namely, the atmosphere, the above-ground crop zone, the soil surface, the root zone, the unsaturated zone below root depth, and the saturated zone (groundwater). Shown in parallel with the behavior of pesticides in these zones is the behavior of water in which most of the movement of pesticides occurs in soils and underlying materials.

The amount applied, an important factor for water-soluble pesticides that are relatively mobile, is not considered here because normally only small quantities are applied per acre. With relatively mobile water-soluble pesticides, the potential for movement to groundwater may be much increased where large amounts have entered the soil, as in areas used for fill stations, tank fill-up areas and sprayer rinsing pads.

Finally, a recent CAST report [1985] summarizes the principle agricultural-related substances of concern in groundwater and recommends a series of preventative and/or corrective actions [Table 3]. In the case of pesticide use, prevention strategies are clearly the cost-effective way in which to prevent either point source or non-point source contamination. Table 4 provides a description of the most common technical terms utilized in groundwater contamination studies. As noted in Table 5, however, there are many contributors to a "contaminated" groundwater and agricultural contributions are but one of many. However, pesticides may be perceived to be the most sensitive and critical from the public perspective.

II TECHNOLOGY ASSESSMENT

There are a number of factors which indicate greater vulnerability to leaching of pesticides. These include:

Pesticide Properties [see Table 6]

- * high solubility
- * low sorption
- * persistence

Soil Characteristics

- * sand and gravel
- * low unorganic matter

Site Conditions

- * shallow soils
- * wet climate or extensive irrigation

Pesticide Management Practices

- * pesticide incorporation
- * poor timing

The U.S. EPA has a listing of threshold values of leaching potential for pesticides. The values in Table 6, combined with the EPA rating, represent a guideline for potential problems and should be taken only as a condition for additional data to document that potential. Placement of the pesticide on particular sites with vulnerable soils is a decision which may be influenced by additional information made available to the user and/or controlled by label restrictions. Thus the specific conditions under which the user utilizes the material represents a significant opportunity for improving pesticide management. There are many factors which determine the specific type and amount of pesticides utilized in a particular season (Table 7) [Cal. 1989]. When used in agricultural systems, a number of factors can influence what happens to the pesticide active ingredient (Figure 3). The exact distribution and pathway for any one pesticide is influenced by many factors and is variable from year to year. However, based on the low amounts of pesticide used/acre, we would anticipate low intrusion rates into the surrounding environment. What complicates this scenario is the fact that depending on the match of the crop, soils, application system, chemical rate and frequency, time of year, etc., the amount of off-target (crop) movement can vary quite widely.

Current/Available Pesticide Management Practices

Information management, technology transfer and increased hands-on training represent the major available means of improving the following available technologies and/or current practices:

1. Establishing the need, method and frequency of controls.
2. Availability of site vulnerability information, i.e., sites near water, shallow soils, or previously contaminated wells.

3. Decision aids in assessing pesticide potential to leach, vs. economics, vs. ease of practice, vs. logistics and available resources, vs. changes in perceived risk, and finally, the necessity for increased management expertise.
4. Essential Best Management Practices (BMP) must be practiced including:
 - * Follow label instructions, and document the application practice and use patterns.
 - * Application at the correct time per recommendations from the farm scout or consultant on correct identification of the problem, crop growth, weather forecasts, etc.
 - * Correct measurement and transfer of toxicants at the fill sites using an optimized approach rather than the maximum label (insurance rate). Use of spray monitors and monitoring the application process so that the tank is empty at the end of the field can greatly diminish the amount of waste being disposed of at the fill-up site. Small nurse tanks can then be utilized to dilute spray mixes remaining in the pump and booms, and the diluted mixture sprayed out on the way back to the spray pads. Here, the tank rinsing process is then accomplished with a greatly diluted mixture and can eliminate major point source contamination.
 - * Application equipment calibrated and tagged yearly with a sticker indicating calibration date. As noted earlier,

the lack of calibrated equipment remains the number 1 problem for effective pesticide management. Now becoming just as important with the introduction of more efficacious new chemistry is the fact that the current equipment cannot easily deliver (consistently) these lower rates with the necessary accuracy.

- * Different fields may require adjustments in both spray volume, and rate of pesticide. Scouting programs can diminish the need for "insurance" applications.
- * Pesticide container disposal is being upgraded (see later discussion), however, the average user clearly needs to spend more time improving this aspect of pesticide management. Extension personnel can, with this and previous items, hold on-farm demonstrations of the proper procedures as part of a "stewardship" program.
- * Pesticide storage and records management are clearly two points where greater attention by the user can assist pesticide management. Records management is not a prime concern for most users and significant opportunities exist for computerized decision aids which can provide users a chance to explore production/cost/crop loss relationships. Access to improved information about the economic status of their operation will also diminish the tendency to insure, i.e., putting it in the tank just to be sure. Sound on-farm economic models are lacking, although the OSU MARKET MODEL does provide a first look

at the potential for greater understanding of changes in the crop production/protection systems for their crops on their farms [Hall, et al. 1987].

- * Proper use of irrigation and better timing of sprays (weather predictions) to minimize excessive movement through the soils.
- * Improved use of ecological selectivity which is the judicious management of pesticides based on selection, timing, dosage and placement of pesticides. Selection in regards to reduced toxicities to known predator or parasites can allow natural organisms to assist the crop protection practice [Hull and Beers, 1983]. In addition, dosages can be chosen on the basis of pest pressure, aided by farm scouting and the identification of hot spots. The use of economic injury levels and pheromone traps as decision aids to better time pesticide applications is also a feature of improved pesticide management techniques.
- * Application equipment technology - see separate paper on equipment (Gebhardt)

5. Biotargeting Concepts

- * The dynamics of the many soil processes to which pesticides are subjected in the soil environment are numerous and complex. If the physical properties of the soil insecticide cannot be exploited by formulation, i.e., controlled release or other formulation adjustments to

reduce solubility and leaching potential, and to optimize dose transfer to target pests to elicit a satisfactory response, then targeting efficiency may be improved through application technology.

- * Groundwater will continue to force attention on the potential for better targeting of soil-applied pesticides. As concluded by Hance [1983], "The theoretical opportunity of improving the efficiency of chemicals by devising better procedures to transfer them to the target site remains a tantalizing technical possibility which justifies continuing research on the physical and biological processes that control the distribution, concentrations and persistence of pesticides in the soil."
- * Problems in certain soils where an increased environmental burden results from repeated applications, premature leaching, or increased applications are challenges that will have to be addressed. One solution to reducing these leaching problems is with the use of controlled release technology with polymers and the use of EVA (ethylene vinyl acetate copolymers) films, incorporated with pesticides with different physicochemical properties.
- * On a more practical basis, Bergman et al. [1986] demonstrated that the density of granular products played a significant role in the pesticide performance, i.e., the more dense granules had less drift potential.

When wind shields consisting of vinyl floor molding were put into place, little if any drift occurred. This relatively simple and inexpensive modification could be accomplished easily by farmers. However, in the absence of meaningful incentives, i.e., well documented economic benefits, and/or regulatory statutes, this simple but effective modification is not likely to occur on the average farm.

- * Wildlife impact assessments for the Environmental Protection Agency are now required for many granule systems in that the efficiency of the incorporation process needs to be documented using ultraviolet light photography of inert fluorescent dyed granules. A recent development by Rhone Poulenc AG was the modification of the intermittent delivery concept of Reichard & Ladd [1981] to apply aldicarb to citrus trees in a localized targeted manner. The conventional means of banding aldicarb granules to a row of trees was replaced by a technique which used an infrared photocell to sense the tree. The system then automatically meters out a quantity of aldicarb granules in two narrow streams and a rolling cultivator behind the unit incorporates the granules. The methodology accomplishes the same biological effect as conventional techniques with significantly less material and was successfully utilized on large acreage in Florida and Texas in 1987 [Hall & Reed,

1989].

- * With granular soil insecticides, the granules require moisture to release insecticide to the soil and furthermore, the release pattern is unlikely to be uniform due to variability in the carrier and the soil. Therefore, a liquid formulation which has higher quality control in its manufacture and is already in a uniform state may significantly increase the effect of targeting. Numerous examples of soil targeting efforts have been summarized by Hall and Reed [1989] and include injection into turf, microtubules for use with low volumes of carbofuran into seed furrows at sowing time [McCracken, 1987], calibration devices and training programs and drift protection/target placement aids [Hall and Reed, 1989].
- * Another example of refined targeting of soil-applied pesticides was air delivery of granular pesticides into 15 cm deep vertical bands in freshly prepared seedbeds prior to lateral distribution [Whitehead, 1983]. This method of application does not depend upon leaching for moving toxicant to soil pests. In addition, the technique is faster than rotary hoeing the soil. Suett & Thompson (1985) describe banding and subsurface treatments, carrier types, and also peat block and seed treatments all designed to more effectively TARGET the toxicant. While soil-applied materials do not exhibit the drift-accountability problems of atomized sprays, they clearly

have unique and mounting problems of groundwater contamination, enhanced biodegradation, application efficacy and accuracy, and predictability.

- * More recent studies of a technology which uses a "rescue" type of approach incorporates the concept of slot injection, whereby insecticides are placed near to developing corn roots for control of corn rootworm - in a timely and only-when-needed strategy [Hall & Reed, 1989]. Insecticides were chosen for differences in water solubility and vapor pressure. These studies demonstrate that the concept (more recently including timely delivery of fertilizer also at reduced rates) shows excellent promise whereby rates of pesticides were reduced to 1/3 of standard at-planting recommendations with no increase in the vulnerability of soils to a leaching problem because of this targeted technology.

In general, greater user discretion and management is needed to reduce pesticide use. This will take increased use of technology transfer techniques, as well as the development of more fundamental information on user awareness of pest conditions and cost/benefit strategies. Carlson [1988] succinctly summarizes the situation "many of the low input agriculture technologies [which could aid groundwater problems] require precise timing and complex input and output devices. Such managerial skills are not costless to develop and maintain." Specific crops (i.e., cotton, tree fruit) have benefited from an IPM approach but still lack 100% participation. Lacking is more hands-on training and improved documentation

of benefits, expectations, awareness of user constraints, etc. Further adoption is now hindered because of economic pressures and the decline of funding for IPM programs. The same (public) pressures creating groundwater concerns, however, could be channeled into an action program documenting the benefits from a decreased "reliance" on chemical tools which can thus be more targeted in a "prescription" approach to crop protection.

Chemical use can be reduced [amount and frequency of chemical intrusion] through integrated pest management strategies and alternative application methods. Crop rotations, crop monitoring, use of resistant varieties, timing of planting and harvest, biological controls, and other management techniques can also reduce chemical applications.

Simulation Computer Models

Reduced pesticide use is an important secondary safeguard, but as Sand (1988) notes, it fails to target those products with greatest environmental risk. A new safeguard is needed that will enable users to easily select products with the lowest environmental risk concurrently with a sensitivity analysis on pesticide benefits to the user to be accrued from that strategy. A model [Pesticide Benefits Assessment - PBA] with this potential has been developed by The Ohio State University and is being utilized within EPA/USDA pesticide benefits assessment programs [Hall and Lemon, 1988]. However, such models could also have economic value to pesticide users themselves so that they may choose an optimized crop protection strategy which might also have consideration for environmental risk. An environmental risk rating could be assigned so that users could factor their concern for environmental safety into their buying decisions [Sand, 1988]. The formula could weigh such factors as chronic and acute toxicity, rates and methods of

application, and anticipated losses to and persistence in the environment. EPA could place such findings on the product label, similar to the code-word system now used to communicate product health risk to pesticide applicators.

Risk ratings could enhance environmental safety as a significant factor in marketing and selecting pesticides. Opinion polls indicate farmers are concerned about environmental safety. As new products are developed, there would be greater financial incentive for chemical companies to market products with lower environmental risk. The chemical industry may not welcome risk ratings, but it can benefit from an independent, objective rating system. Buyers who are given these facts would be less apt to overestimate the risk of a product because of adverse media coverage or other fears. Also, a scientific system for prioritizing environmental concerns would make EPA procedures less subject to political pressures and shifts in public opinion. Risk ratings would also give individual buyers greater control over the environment where they work and live. Buyers who select products with lower risk may experience reduced liability risk from off-site pesticide contamination.

Other models involving tracking pesticides in soils and developing predictive capability of pesticides within soil ecosystems [Haith, 1985]. Analyses of water quality surface waters require estimates of runoff loads of pesticides. Two different types of estimates are often needed, mean annual or seasonal loads and "critical" loads. Mean loads are useful in regional and screening studies to determine general pollution levels and evaluate management alternatives. Critical loads are exceptional pesticide inputs that may have major water quality impacts and occur rarely, but

which can be the basis of risk assessment of water quality.

Monitoring data are seldom adequate for either of these loading estimates. An obvious alternative to monitoring is the use of a Monte Carlo simulation process to produce a random sample of pesticide loads for calculation of mean loads and probability distributions. However, modeling depends upon accurate mathematical descriptions of chemical behavior and an efficient means of generating the weather data required for long-term simulations [Haith, 1985].

Ranking pesticides provides a basis for relative comparisons as to potential for groundwater loading. However, they are not specific to the soil, management system, or climatic situation of interest. Leaching of pesticides from the plant root zone will depend on rainfall (or irrigation) amounts and distribution immediately after application. Soil properties and soil management affect the partitioning of rainfall between surface runoff and infiltration, and soil properties also affect water and solute retention. Therefore, Leonard and Knisel [1988] conclude that it is as important to rank soils and management practices for leaching potential as it is to rank pesticides.

Leonard and Knisel [1988] summarized some of the working comprehensive mathematical models developed to evaluate specific soil/pesticide/management/climate combinations to date. These include:

* CMIS, Chemical Migration in Soils -

A management model used to demonstrate pesticide response (educational)

* PRZM, Pesticide Root Zone Model -

U.S. EPA model used to aid pesticide registration decisions

*** GLEAMS, Groundwater Loading Efforts of Agricultural Management Systems -**

An extension of the USDA CREAMS model (Chemicals, Runoff, and Erosion from Agricultural Management Systems) used to evaluate scenarios affecting pesticide transport through root zones and surface runoff.

*** LEACHAMP -**

Leaching model for pesticides which is used to improve understanding of system processes.

None of these models to date give absolute predictions and each requires comparisons of known conditions to judge relative effects. However, recent studies by Khan and Liang [1989] proposed that a GIS [geographic information system] strategy could be effective in evaluating contamination potential for pesticides with the use of the attenuation factor (AF) i.e., likelihood of groundwater contamination computed on the basis of % of applied chemical leaching beyond surface soil layers. They conclude that the management approach (based on testing) is not sufficient and recommend establishing standards and procedures for restricting chemical use on certain sites, perhaps by a license for use in certain cases designated for specific cropping patterns.

III OBSTACLES TO IMPROVEMENT

An investigation of the obstacles to improvement in the current status shows the following represent the major hurdles for a quick solution:

1. The ecosystem is a complex phenomena with many interacting parts, many of which are not yet identified or quantifiable.
2. A recent "white paper" by the AICE [1986] on groundwater problems identified the following obstacles for improvement:
 - a. Confusion about which agencies should deal with the problem. Thus we have
 - b. duplication of effort,
 - c. uneven implementation of statutes and a
 - d. lack of accountability for the problem.
3. In addition, AICE noted that in addition to the federal agencies and ca. 100 state agencies involved in the issues, a lack of total resources for monitoring, testing and sampling hundreds of new chemicals has also contributed to the problem.
4. A shortage of scientists trained in environmental problems are also stumbling blocks.
5. Addressing EPA specifically, Dowd [1988a] presented a critique of EPA's lack of direction in handling environmental pollution problems. Dowd also provides further evidence of the scope of the problem by suggesting that EPA pesticide decisions currently:
 - a. have enormous data gaps in knowledge base on the (1) impact on ecological systems, and (2) chronic effects.
 - b. There is an overemphasis on synthetic vs natural
 - c. Technology transfer is weak

d. There is a lack of fundamental understanding of the next generation of environmental problems, i.e., a lack of predictive capability.

6. Carter [1989] concludes that the government programs which provided incentives for high-input farming [now thought to be contributing to groundwater problems] were devised in a cheap energy era and remain intact today. Society is, in general, weaned on a "throw-away" philosophy with little regard for the externality costs. Carter suggests that the premium [profit for growers] for cosmetically appealing fruits and vegetables makes it difficult to produce and market profitably without chemicals. Thus, government programs and societal demands have to be reconciled to affect society and the people in it towards a more informed public on environmental safety and inexpensive, abundant, and quality foods.

Dowd [1988a] concludes that these problems facing EPA and pesticide decision making are a result of (1) too many problems and EPA with limited resources spends too much time fighting fires, (2) short term statutory mandates are the basis for EPA actions, (3) team approaches are needed but interagency politics intercede in a cost-effective approach to environmental problem solving, and (4) there is a lack of top management involvement and leadership.

There is a failure to recognize that although innovative pesticide chemistry has allowed a reduction in use rates, the necessity for a comparable accuracy in delivery has just not been addressed. This failure has been identified and emphasized in a series of ARI sponsored meetings

whose objective was to document the lack of attention by policy makers.

PROGNOSIS

The Search For Solutions

If we are somewhat limited by what can be done in the corrective area, we are not so limited in the preventative area. Pesticide use continues to grow in the U.S., fueled largely by an affluent society and the demands for an abundance of an inexpensive, safe, high quality and plentiful food supply. Analytical techniques are capable of detecting pesticides at concentrations far below those of biological significance. When no official guidelines are established, however, members of the public are not inclined to accept any concentration as safe, no matter how low it may be, because they have no basis for judgment. These conflicts pose a serious concern for those attempting to develop rationale strategies for pesticide management. Dowd (1988b) comments that the EPA strategy for the 1990's [EPA, 1988] is a plan which based on the previously identified weaknesses, does focus on a waste reduction strategy and holds more hope for improvement, especially with ecological research, and a planned environmental research strategy.

Environmentalists frequently perceive such events as groundwater contamination [at any level] as a golden opportunity to persuade governments to adopt their current wish list. This case is weakened, however, by appeals to uncertain apocalyptic scenarios, i.e., poisons across our landscape, in our water and food, in their desire to influence Congress into acting prematurely. Our regulatory statutes must reflect sound science rather than questionable prognostications. Clearly, a part of any future series of policies must be the engagement of the public/policy makers in a higher degree of communication about the findings of groundwater surveys,

the meaning of such levels and the development of a public awareness about trace levels of toxicants and the concept of dose response, referring to common chemicals with which the public is familiar - i.e., aspirin. The Ames Herp Index [Ames et. al, 1987] (Figure 4) would be useful in developing this public awareness. Since public funds and support are needed in any strategy aimed at environmental programs, their understanding and support is clearly a first priority.

A focus on pesticide management practices which may be useful in aiding groundwater protection suggests that there is a logical grouping of "needs" categories to include: advances in technology, a transfer of that technology, information management, policy needs/incentives, and increased resources for research.

Specific strategies could focus on:

- (1) Optimization of current practices which could minimize groundwater contamination. A more accurate estimate of the specific field requirements of a pesticide could eliminate (A) over spraying, and (B) contamination of fill-up areas because of the dumping of unused materials. The use of on-board rinse water (as a safety item as well as dilution) could allow farmers to dilute the remaining 5-8 gallons left in the tank/booms/pump and spray out the diluted material onto the field on the way back to the rinse pad. Rinsing procedures at the pad then are left with greatly diluted mixtures. Other optimization techniques could involve more intensive use of integrated pest management techniques, using pheromone traps, scouting, and other trapping and

decision aids to allow for improved timing of pesticides. Pest predation models can also significantly aid the timing of crop protection measures. These might include prognosis models, economic threshold and injury models, crop loss models, prediction of pathogen or aphid intensities, etc. [after Doyle et al., 1988].

- (2) Technology Transfer includes the improved use of already developed techniques in alternative cropping, tillage programs, and calibration/monitoring programs. Knowledge already exists for the improvement of cropping and innovative protection strategies. What is missing is the necessary "hands-on" assistance at the farm level and the proper incentives to accomplish these tasks.
- (3) Incentives for Change can be an additional aid for the implementation of new strategies. Initiatives thought to stimulate ACTION and which have a major impact on ultimate courses of action taken by an individual or organization include:

- * PROFIT - reduced costs
- * REGULATION - groundwater, air quality, waste, etc.
- * LIABILITY - Proposition 65, etc.

What is already ongoing in Europe on pesticide application equipment represents some fundamental safety innovations. Lamphier [1985] and Simmons [1988] presented elegant discussions about innovative commercial technology in agriculture and the need for assistance in developing that technology via various federal programs, including a greater utilization of the Technology

Transfer Act, etc. Tax incentives [i.e., for grower purchase of groundwater protection devices] and/or increased pesticide registration fees [re: Iowa Groundwater Act, Hall, 1985], and/or user fees of 1-2 cents/lb of pesticide utilized could significantly aid these problems currently associated with a less than optimal pesticide management. Tax incentives and/or regulatory pressures add to the rate at which new technology is accepted. Another example is the Canadian Food Systems 2002 project. This project has allocations of \$10 Million for RESEARCH on spray technology, systems approaches and IPM, under a competitive grant process, and \$12 million for EDUCATION on Pesticide Application Technology (PAT) handling and safety thrusts, and \$3.4 million aimed at FIELD DELIVERY OF THE INFORMATION. In brief, the project would (1) cut current pesticide use by 50% over the next 15 years (also mandated in Sweden, Denmark and some US states already, (2) gives an 80% CREDIT on the purchase of some safety items, e.g., fill devices, clean water carriers, self-clean filters, cabs, etc., (3) recognizes that not enough is given on the label relative to a "prescription usage," and (4) allows the Ministry to go onto the farms to check on storage, disposal, safety, etc., and can levy fines where appropriate.

(4) Infusion of New Application Technology. At the present time, PAT is static because of a declining market. The Technology Transfer Act has not been fully utilized in agricultural pesticide management and thus opportunities remain untapped for significant improvement of pesticide application management [ARI, 1988].

(5) Fast Track for Biorationals. Pheromones, viruses, bacteria, fungi, and/or bioengineered natural organisms have been

touted as biorational alternatives to conventional pesticides. However, current EPA policies in practice have not allowed rapid utilization of these techniques/alternatives into commercial realization which could reduce the amounts of conventional pesticide available for intrusion into groundwater.

- (6) New Knowledge. Additional information is clearly needed in order to define which chemicals pose the greatest threat to which soils and under what circumstances they should be avoided.

User Management Techniques

Management practices that minimize the movement of agricultural chemicals into groundwater is a multi-faceted challenge, involving complete toxicological risk assessments and federal establishment of health advisory levels for agricultural chemicals in water for human consumption. In addition, the development of reliable sampling and testing procedures and predictive models that will aid in identifying potential problem areas and alternatives which can be used to minimize adverse effects will also be effective new technologies. Already available for use in aiding protection of groundwater but which need additional support for training from state, federal, and private organizations includes the following items: (1) strict adherence to label instructions; (2) proper use of carefully calibrated specified spraying equipment; (3) prevention of back-siphoning into water sources; (4) mixing of pesticides away from drinking water sources; (5) proper pesticide and container disposal practices; (6) proper timing and control of irrigation in accordance with rainfall; and (7) proper well

construction and location [NACA white paper on BMP].

Deviation from label instructions can result, not only in adequate performance, but, depending on the degree of deviation, in increased potential for the movement of those agricultural chemical residues into groundwater. Proper timing, placement and rate of application, as specified on the label, are extremely important. The tendency to use excess chemical, based on the thinking that, if the recommended amount will kill the pests, then higher rates will be even more effective, must be avoided. Excess pesticide use will not do a better job of controlling the pests, and may increase the odds for percolation of residues into groundwater. Most growers do not intentionally exceed recommended label rates; however field checks have shown that improper sprayer calibration has been a problem (Hall, 1985).

Perhaps the second most important factor in attempting to prevent movement of agricultural chemical residues into groundwater is proper management of the various water sources, both natural and artificial, occurring in our environment and available to farmers for crop usage. Following controlled irrigation practices from the standpoint of both quantity and timing, as set forth in label instructions, is very important. Excessive amounts of water can increase both the amount and rate of percolation of a water soluble pesticide through the soil into groundwater. It can also increase runoff of trace pesticide residues that are either dissolved in water or attached to suspended soil particles eroded from treated areas and then subsequently deposited in nearby streams and lakes.

IV. RECOMMENDATIONS

How can we improve the current status of pesticide management? An array of strategies which can potentially be effective are as follows:

- (1) Improve the understanding of the nature and scope of the problem:

- a. develop a systematic database on vulnerable sites
- b. develop scientifically based sampling protocols

Utilizing information already known, in hand, or being tracked (by paper records), is clearly not being accomplished. Much of this could be achieved by use of computer models such as Pesticide Benefit Assessment models [PBA] [Hall and Lemon, 1988] being developed for pesticide use/benefit assessments. Such models allow the potential for identifying data gaps and developing strategies which when externalities on environmental "costs" are included in the analysis, could provide a unique tool for the assessment of IPM, or other pesticide management techniques, alternative cropping strategies, or regulatory risk policies.

- (2) Establish data needs for this understanding

- a. require characteristics of pesticides that determine the probability of leaching (currently being developed by industry, but not yet integrated in pesticide management strategies).
- b. develop complimentary characteristics of the soils, vadose, and aquifers.
- c. identify locations where pesticides of concern are used and in what quantities.

- d. locate vulnerable aquifers and accompanying cropping patterns.

Drawing conclusions from database summaries should be done with caution, because the distribution of information types and sources may be unknown. Aggregation of information can also obscure subtle influences affecting trends. In spite of limitations, the database approach for working with large information sets is useful [Theiling and Croft, 1988]. At its current rate of expansion, scientific information is difficult to integrate and use creatively. Identifying trends and characteristics of this information base is a powerful use of database technology which can yield new perspectives and help pose appropriate questions, a strategy which Dowd [1988,a,b] suggests is badly needed in order for EPA to more fully develop this mandate. On the other hand, industry has not yet optimized information management to aid its predictive capacity for groundwater sensitivity (to pesticides).

(3) Focus on elimination of point source contamination

Frequently the use or spillage of agricultural chemicals around wells can contribute to the presence of residues in drinking water. One common cause of this is back siphoning from spray equipment into the well. It should be required that pumping equipment must employ an anti-backflow device when drawing pesticide mix water directly from any water source. Improper land disposal of empty containers, or of excess unused pesticides, can easily cause an eventual localized groundwater problem in the area of disposal.

The development of regulatory restraints and the growing sensitivity of

pesticide producers to the problem (and to potential liability) suggest that directions for pesticide use will increasingly be written with an eye toward avoiding groundwater problems. Specific suggestions for minimizing point source pollution from agricultural chemicals include:

- * Mixer Loader - clearly at most risk in the chemical use process and represents an opportunity for a more precise transfer (no touch system) (addressed later in recommendations).
- * Safety devices to prevent backsiphoning is clearly a technology already available, but economic incentives could be installed to aid 100% compliance/ usage.
- * On farm storage poses a problem for many growers. Many storages are isolated and well identified. However, storing only "as much as needed" as a strategy creates a problem of dealing with other techniques which ask users to wait until a proper time to treat. Emergencies and poor weather windows then create chaos in attempting to deliver needed chemicals to the crop when they are no longer being stored on the farm in anticipation of the need. Current "early season buying incentives" offered by industry also conflict with minimizing storage amounts. A more effective strategy might be to address the quality of that storage, provide incentives for its upgrade and educate users about storage hazards and the economic benefits of planning/goal setting for next year's production strategies.
- * Pesticide Waste Disposal - A serious problem which is being addressed by the ARI ACTION recommendations (outlined in detail later in the paper). Clearly this is an item where industry, EPA

and other federal agencies can do much to improve the current disposal problem in the short run. "Minimize the amount of waste" is the cost-effective approach for improving the situation. Tools and practices needed to accomplish this task need further research but information delivery and training at the farm level are an essential part of the solution. Additional needs include the more rapid development of cost effective waste effluent treatment plants such as the ICI Sentinel System, which could be utilized on large farms and custom operations where large amounts of pesticide are being transferred and tanks rinsed at the fill-up pads. Federal grants can aid such developments, but are slow in filling these needs in spite of the public outcry against excessive point source problems.

* Well contamination can be avoided by several simple, common sense strategies. These include:

- Not allowing storage or mixing of agricultural chemicals closer than 500 feet from a well. Do not leave sprayer while filling tank. Rinse tanks according to standard guidelines and never dump extra mixes onto the pads. Use spray-out procedures to dispose of remaining mixes.
- Rinsing routines standardized and practiced on pads 500 feet away from wells.
- Dilution and/or water recycling measures need to be investigated.
- Use of soluble bags and/or returnable systems can reduce cleaning and waste disposal, but needs additional resources

for research to maximize its potential and the waste problem. User incentives may be an effective strategy.

- Utilize well inspection practices.
- Plug and cap abandoned wells.

4. Pesticide use restrictions

Along or in combination with adjustments in other agricultural management practices, use restrictions will continue to be the primary approach to addressing contamination problems. The National Academy Report on pesticide issues [NA Press, 1986] concluded that the most urgent actions needed to address groundwater problems arising from field-applied pesticides appear to be:

- * Federal determination of health-based standards for pesticides in water;
- * The development of improved, multi-residue analytic tools for screening groundwater for pesticides at the parts-per-billion to parts-per-trillion range;
- * The development of a systematic monitoring program;
- * The development of improved models of pesticide behavior and fate in soils, the vadose zone, and aquifers, and assessment of their validity under field conditions;
- * The development of data on environmental fate and pesticide use patterns, in conjunction with local hydrogeologic conditions, at a level of specificity adequate to identify areas especially vulnerable to groundwater contamination and to develop site-specific restrictions on pesticide use; and
- * The integration of groundwater resource considerations into an array

of agricultural management practices and choices, including cropping, tillage, irrigation, and pest management. What it will take is a systematic hazard rating system (Figure 5) capable of assessing soil vulnerability, coupled to pesticide delivery efficiency data (by application method), runoff, drift, and volatilization potentials. The integration of data from predictive models and actual field studies on previously identified susceptible sites will verify model usefulness, as well as prioritizing the most hazardous pesticide/soil rate/application scenarios. At that point, the appropriate agencies can focus limited resources on those sets of combinations for potential restrictions on pesticide use.

5. Improvement in Pesticide Application Technology

For the past 5 years, agricultural leadership has continued to emphasize the problem of PAT not keeping up with advances in pesticide chemistry and thus contributing to an inefficient delivery of pesticides into the environment. Koskinen and McWhorter (1986) recently observed that new developments in PAT continue to be slow -- "research is at its lowest point in 20-30 years." Thus, what should we be doing to correct this paradox? - a perception that we are placing too much in the environment and yet, research dollars to solve the problem (and it can be improved), are lacking.

On the other hand, it is risky to assume that new technology will automatically be accepted (and utilized). In a survey of pesticide users, Smith [In Hall, 1990] concluded that predicted advances in PAT (which might alleviate groundwater intrusions) showed only moderate acceptance of new technology. Thus, in the absence of a clearly targeted regulatory policy, unless benefits [incentives or reduced liabilities] are clearly identified,

traditional methodology is perceived as acceptable by pesticide users. But, Bohmont [In ARI, 1988] shows that users are not using current equipment to best advantage with a very large error in the "intended rate" in spite of increased attention to proper use practices. Consequently, more of the same old technology transfer presentations are not going to solve the problem. The forum on Regulatory Decision Making: Problems and Prospects [IUPAC, 1986] provides good background material on the conflicts of various approaches for those intending to regulate, provide incentives, institute taxes, etc., in an attempt to tighten the pesticide use patterns for the benefit of society in general.

"Improving Agrochemical and Fertilizer Application Technology" was the title of a Conference sponsored by the Agricultural Research Institute (ARI) at the National 4-H Center in Chevy Chase, Maryland, February 27 - March 1, 1985 [Hall, 1985]. Specific needs identified at the Conference included research on: (a) new and improved agricultural chemical application technology with an emphasis on basic concepts, and (b) movement of chemicals from target sites via drift through aerial transport, water transport and other mechanisms.

The Objectives of the 1988 ARI Conference were:

1. To identify the primary problems associated with the application of chemicals.
2. To identify innovative approaches and define fundamental research necessary to improve application technology.
3. To differentiate private and public sector responsibilities with regard to research programming, development of innovative technologies and program funding.

4. To describe or evaluate risk management practices associated with new technologies.
5. To define policies, educational needs and programs to improve the efficiency of chemical use in agriculture.

The general consensus of attendees resulted in four major conclusions:

1. There is a critical lack of sufficient interdisciplinary research in agrochemical application technology.
2. Research in application technology does not have a high priority for funding in spite of: (a) public concern regarding various forms of potential environmental contamination such as groundwater intrusion of agrochemicals and off-target movement (drift), and (b) the need for precision application of chemicals possessing high biological activity, including products of biotechnology.
3. Advancements in chemical technology are rapidly outdistancing application technology, partially because of (a) depressed equipment sales and insufficient financial incentives to conduct fundamental research by the application equipment industry, (b) a serious lack of basic information about the application process and (c) inadequate communication between the user of chemicals, the manufacturer and the researcher.
4. There is an apparent lack of adoption of innovative technology and engineering concepts from other sciences and industries.

Specifically, 8 major concerns of pesticide application technology were identified which are associated with potential groundwater contamination.

- * Research in application technology has failed to keep pace with recent trends in agrochemical development and/or utilization.
- * There is a serious lack of administrative support for interdisciplinary agrochemical application research funding and research by and within federal and state agencies to facilitate measurement, prediction, targeting and placement of agrochemicals and fertilizers.
- * There is too little emphasis on chemical user awareness and education in technology transfer.
- * Off-target movement (drift from target site) is not being addressed adequately and methodologies to prevent drift are lacking.
- * Airblast sprayers are too limited in practical adjustments for both delivery rates and distribution patterns.
- * Equipment for simultaneous application of pesticides and plant nutrients is inadequate to meet future agricultural needs.
- * The understanding of environmental and ecological relationships which permit improved prediction of chemical delivery is minimal.
- * Precise identification of environmental safety guidelines such as waste resource contamination from runoff, is lacking.

V. SOLUTIONS/ISSUES FOR ACTION

Specifically, we can place the issues into several categories:

1. Technology Advancements
2. Technology Transfer

3. Information Management
4. Policy Needs/Incentives for Action
5. Research Needs

There appear to be some commonality among the issues, i.e., educational needs, additional resources, but even more important, an improvement in the "use of what we already have in hand." Several conferences have addressed the various research needs and attempted to prioritize them. Policy analyses are needed to assure continuity/farming policy/regulations, etc., and to insure that the regulation/policy does indeed do what was intended. Science in general, needs to be placed in the public eye on a more credible level. The public clearly is/has been misled by headline seekers and now is confused over just what pesticides in groundwater or on foods really means in terms of their daily life [Figure 6]. There is a clear lack of definition over what constitutes a hazard in terms of parts per million or billion [PPM/PPB]. This headline sensationalism promotes vigorous discussions and opinions and outcries for ACTION, but at the expense of the farmer, and ultimately the taxpayer, which results in an array of (often conflicting) regulations. The affluent U.S. society does have a price for this well being and thus we need to build in an increased environmental awareness sensitivity. The "throw away" philosophy currently well endowed in the U.S. does indeed have a price [clean-up] and thus prevention [of pollution] strategies are viewed as the only way to treat environmental problems. The selling of this philosophy should be a major effort for policy makers. Are there factors or actions which can stimulate positive results without resorting to regulations?

The 1985 ARI Conference recommended the following ACTIONS were needed:

1. The Assistant Secretary of Agriculture for Science and Education, U.S. Department of Agriculture; Director, Office of Technology Assessment, U.S. Congress; and the Science Advisor, Office of Science and Technology Policy to collaborate in organizing, under the sponsorship of ARI, and participate in a forum of federal, state and industry policymakers to:
 - (a) define the obstacles that inhibit the development of improved application technology for agricultural chemicals and biological agents;
 - (b) establish research priorities that will respond to current problems;
 - (c) develop plans for the establishment and funding of research centers of excellence and define appropriate coordination responsibilities and mechanisms; and
 - (d) examine mechanisms for fostering interdisciplinary research activities within and between industry, government and academia.
2. Develop a plan to resolve the problem of inadequate funding for application technology research through a series of leadership meetings which would include leaders from ARS, APHIS, EPA, CSRS, industry, academia and user groups. Models to be examined might include:
 - (a) the identification of a support for "Centers of Excellence" at sites where research on various aspects of agrochemical application technology is already established and partnership linkages with the chemical and equipment

industry have been initiated. This would accelerate fundamental research, increase information distribution and promote faster utilization of research information for developing new technologies and equipment;

- (b) development of a research fund created by contributions from chemical and equipment industry members with a possible partnership fund from federal agencies;
- (c) the IR-4 type approach to problem solving in the agrochemical application area;
- (d) a joint industry effort to establish an industry institute similar to the Chemical Industry Institute of Toxicology (CIIT) in Research Triangle Park, North Carolina. In this case, the "Institute" would deal with fundamental principles associated with the complex process of agrochemical application; and
- (e) a competitive grants program favoring multidisciplinary research projects on fundamentals and new concepts for improvement of the efficacy of application technology.

3. Improve the level of information exchange communication and coordination of research on application technology in the United States.

A follow-up ARI meeting "Spraying On-Target Placement of Pesticides" was held in 1988 to identify and prepare realistic solutions to concerns about placement efficiency. Three principle concerns were discussed and action plans presented to policy makers in USDA, EPA, and NACA in early 1989.

They include:

A. PESTICIDE HANDLING, PACKAGING, AND TRANSFER

Problem: Pesticides are currently packaged in a wide array of containers. These vary in material, size and shape which create problems for users in pouring, compatibility with closed loading systems and storage, and rinseability after use. In addition, they represent significant disposal problems for the user.

Proposal: Organize a committee of executive heads composed of various groups representing EPA, ASTM, NACA and USDA (but not limited to those groups) to develop and recommend guidelines for pesticide containers and handling/disposal of wastes.

In view of the new FIFRA, it is recommended that the aforementioned committee be established in early 1989 and that its suggested guidelines be forthcoming within a year of the date that the committee is established. In order to succeed, such a committee would require the time of individual experts who can and will serve, with a key person to oversee, coordinate and follow up on any actions it may undertake. Funding from federal agency sources for committee activities has not yet been achieved. Specific activities designed to reduce potential point source pollution and worker exposure risks were:

1. Container standardization
2. Package disposal
3. Disposable packaging
4. Reporting System for Exposure

B. IMPROVING APPLICATOR TRAINING

PROBLEM: Pesticide Application Technology (PAT) training programs are not reaching many of the end-users who are performing the actual applications. Certification programs for handlers of restricted-use products are typically reaching only one member of an organization or farming family. Current funding limits at the federal and state levels do not permit expansion of the training programs to reach all applicators. The resulting lack of training is contributing to misapplication which adds an extra cost to the grower and results in non-compliance to regulations.

PROPOSAL: A committee would be formed, and sufficiently funded from federal agency sources, to improve and update a training program to reach all applicators of pesticides. The program should be self-paced and user-friendly using technology available today to minimize the manpower needed for the actual training sessions. There is no financial commitment from government agencies to fulfill this goal as of the date of this report.

Proposed Activities:

1. Foremost to raising pesticide applicator technology training (PAT) to a higher level of proficiency, most, if not all, of the following goals should be accomplished:

- A. Convincingly communicate the tie-in of application technology with good agricultural management practices to the grower and demonstrate the economic dividends to be gained by the user.

- B. Increase public relation efforts on PAT to the public, the Congress and federal and state agencies through agricultural and environmental organizations.

C. Communicate existing technology to the end user by converting data into field case formats. Establish national awards and incentives for demonstrating good PAT.

D. Establish pesticide application technology as a separate curriculum in our universities and establish and adequately fund and staff Centers of Excellence.

E. Require equipment certification as a part of label compliance.

F. Develop better dialogue between opposing agricultural and environmental groups by directing sound PAT to the public's concerns on groundwater residues and drift. Included will be the goal of improving communication/cooperation between chemical companies, equipment manufacturers, universities, federal and state regulators and agricultural and environmental interests.

G. Further roles that chemical companies, spray equipment manufacturers, other private sector groups and universities should carry out in enhancing pesticide application research and technology:

- (1) To assure a continued supply of trained experts in "state of the art" technologies, private industry should expand its support for funding fellowships and grants promoting research in PAT.
- (2) Conduct additional research in the narrow droplet size range, atomization and injection systems of formulations.

C. AERIAL APPLICATION

Problem: Aerial application of agricultural chemicals in support of agricultural production and the pest control needs of farmers, the pest control programs of federal, state and county governments is quite

substantial (ca. 35% of all chemicals offered).

In reponse to the growing public concern and in recognizing its responsibility to minimize the potential for adverse health or environmental effects of agricultural chemical application from possible effects of spray drift, the National Agricultural Aviation Association developed Operation SAFE (Self-regulating Application and Flight Efficiency). However "State of The Art" procedures regarding drift containment, waste disposal, rinsing, packaging and container transfer and handling must be developed to encourage aerial applicators to employ Operation SAFE with a feeling of confidence that drift and environmental contamination are being held to the absolute minimum. Funding for research and education remains the barrier to accomplishing these objectives.

Proposal: Establish an independent body at a Center of Excellence for pesticide application technology to receive funds from industry, government, user groups and others to solicit review and award grants for research and education programs to universities and federal and state research centers that will develop "state-of-the-art" aerial application of pesticides.

Proposed Activities:

1. Develop field useable information from data and models already available regarding particle behavior in the environment that can be used as an aid to educators and regulators.
2. Intensify efforts to standardize measurements of driftable particles leading to the establishment of drift measurements defined as actionable levels making use of field data already available.
3. Identify and disseminate available operational solutions to drift problems and encourage their immediate adoption throughout the aerial

application industry. Examples: automatic flag drops, smokers, specific formulations and constant site weather monitoring.

4. Incorporate results of research on field operational procedures concerning drift into educational programs which target the pilot/operator, regulator, educator and the concerned public.
5. Increase efficiency of aerial application by controlling the range of droplet sizes and by developing delivery devices that are target specific for a specific pest.
6. Environmental Protection
 - A. Good management practices should be used on-site such as recycling from controlled storage and using devices or systems that assure thorough clean-out of residual product.
 - B. Research on and adoption of clean-out systems such as charcoal filtration, etc.
 - C. Current regulations concerning pesticide use should be modified to encourage the adoption of existing technologies.
 - D. Further studies should be conducted in detoxifying pesticide waste water.

SUMMARY AND CONCLUSIONS

Clearly, there are opportunities to improve pesticide management by using what users already know and have as resources. A perceptive integration of INCENTIVES along with coordinated federal agency's agriculture policies would encourage the full utilization of such tools and decision aids. Dowd [1988a,b,c], Hallberg [1986] and Lave and Males [1989] provide stimulating commentary about how to address this complex problem.

Clearly, a focus on point-source pollution associated with pesticides can be accomplished with new, innovative training programs and perhaps incentives for protective devices and strategies. Non-point pollution from general pesticide use has to be accomplished first on vulnerable sites with identification, risk assessment, and perhaps, restricted use patterns. Again, coupled with additional pesticide management training, much can be accomplished in a short time frame. The EPA groundwater strategy suggests that the role of the user is critical [Dowd, 1988c]. It would seem that training could be accomplished much more quickly than the complex multi-level decision process now expected for 600 compounds in hundreds of counties. Lave and Males [1989] suggest (1) EPA and other agencies cooperate on a comprehensive quality analysis of the impact of legislation and compute "best" estimates of risk and benefits (of strategies), (2) that the Council of Environmental Quality be reinstituted with a more vigorous mission on environmental truth telling, (3) that Congress charter the National Research Council to develop research goals for agencies (via cost/benefit, or risk-based framework) to permit legislation to be implemented uniformly, i.e., trade-offs must be well identified. In summary, training the user and providing economic incentives (for IPM, water quality [and conservation]) in a flexible and creative package for the U.S. farmer in a more holistic approach to identifying, quantifying and alleviating agriculture's contribution to groundwater problems [Hallberg, 1989].

Resources and funding for Centers of Excellence to further the research and development of advanced PAT has to be committed because critics of current agricultural policies continue to berate the "perceived over -

insurance" attitudes of the U.S. farmer. There remain many problems which need to be addressed but a focus by policy makers on the recent 3 ARI recommendations [P. 38-45], should allow significant gains to improving pesticide management in the shortest time frame, while at the same time providing significant reductions to the POTENTIAL contamination of our groundwater. Moreover, these 3 ACTIONS simply make good sense! The farmer (particularly horticultural crops) is caught in the middle where the buyer [wholesaler, consumer, etc.] demands high quality [thus yielding a price incentive] produce. Poor quality produce is left on the shelf and/or is hard to sell to the wholesale broker even at substantially lower prices. Organic farming, while having a unique clientele for their products, is not viewed as having a major impact on the marketplace in the next 10 years. WHO will pay for the incentives to reduce pesticide use on crops where multiple pests presently cause havoc with crop yield and quality?

In short, 3 simple tasks are required:

- (1) Identify who is doing what and coordinate potential pesticide management activities on a high level. The activities of multiple agencies each doing their own thing does not lead to a cohesive and/or effective national policy for improved pesticide management. Discussions about policy matters and the implications of policy decisions must be integrated at the highest level. Pesticide Use Strategies, regardless of the level, if they are to be accepted and implemented by the farm clientele, must have benefits of such strategies well identified at the user level. Documenting the impact of a changed strategy has to be given a major role in changing the course of certain practices (or use of certain chemicals) which have sensitive environmental references beyond the farm fence line [in distance

and time]. Duplication of federal effort has only resulted in a frustrated farm clientele, unsure of "who is doing what for whom."

(2) Second, provide adequate funding for development of pesticide management strategies such as decision aids, pesticide [or biorational] application technology, pesticide applicator calibration training, risk management techniques, etc., via the three ARI recommended ACTIONS. To get them implemented by 1990 will greatly further the course of an optimized pesticide use strategy for the U.S. farmer. The needs in PAT, for example, have been documented for the last 10 years and yet the USDA has yet to deliver a comprehensive grant program supporting integrated team approaches to problem solving in pesticide application management. Funds can be generated by an array of techniques, but clearly, the chemistry has gone far beyond the capacity for equal excellence in delivering and targeting that chemistry. The leadership for a comprehensive PAT/Pesticide management set of strategies has just not been developed. A documentation of economic and social impacts of the changing cropping/management strategies has to be integrated rather than regulated into the farm sector which is what would result from the pending Waxman/Kennedy Bill.

(3) Increase the level of communication about pesticides, groundwater and technology to the general public via a coordinated multiagency Task Force. We have a disarming delusion about what constitutes a risk with regard to "chemicals in the environment" and a totally inaccurate conclusion that synthetic is harmful and natural is safe [Figure 6]. Such misconceptions have to be addressed if we are to implement realistic solutions for optimized pesticide management for U.S. farmers in the 1990's.

"In our society, the issue of risk from pesticide use is one where the

level of public information is low and the potential for anxiety high -- a situation likely to confound the policy-making process. We do not have the luxury of discarding the "chemical tools" necessary for control of the many pests that threaten our food supply and health. Therefore, the task for agricultural scientists and policy makers is to effectively communicate risks and benefits impartially to the public. Only through such a process can we hope to retain the public's confidence in our abilities to safely use pesticides. To that end, universities, industries and governments must commit resources to the conduct of essential pesticide research; research that will meet the needs of the Nation's agricultural, industrial and public health programs." [Young, 1986]

Table 1. Major Sources of Groundwater Contamination by Synthetic Organic Chemicals [after Bacon and Oleckno, 1985].

Waste Disposal Sources	Non-Waste Disposal Sources
Landfills, Surface Impoundments, Dumps	Abandoned Wells
On-Site Wastewater Disposal Systems	Accidental Spills
Land Treatment of Municipal and Industrial Wastes	Over-Application of Agricultural Chemicals
Land Application of Sludges	Petroleum Exploration and Development
Underground Injection Wells	Above and Below Ground Storage Tanks

Table 2. Behavior of Water and Pesticides in the Atmospheric and Soil Environments [after CAST, 1985].

Environment Zone	Water Behavior	Pesticide Behavior
Atmosphere	Addition by evaporation from land and water surfaces, transport by air movement, and sprinkler irrigation. Loss by precipitation, transport by air movement, condensation, and sprinkler irrigation.	Addition by application, volatilization from plants and soils, and transport by air movement (drift). Loss by deposition on plants and soils, transport by air movement, and decomposition by sunlight.
Above-ground crop zone	Addition by precipitation, sprinkler irrigation, and condensation. Loss by throughfall, evaporation, and transpiration.	Addition by application to foliage and by transport by air movement. Loss by volatilization, throughfall, wash-off, and decomposition by sunlight and plant metabolism.
Soil surface	Addition by precipitation, lateral movement on the surface, irrigation, condensation, and upward movement from the zones beneath. Loss by evaporation, lateral movement on the surface (run-off), and movement into the zones beneath.	Addition by application to the soil, transport by air movement, throughfall and wash-off from plants, lateral transport on the surface, and upward transport from the zones beneath. Loss by volatilization, lateral transport on the surface (runoff), and transport into the zones beneath, and decomposition by chemical and biological means. Retention by the soil.

Root zone
(unsaturated
soil)

Addition by movement from the
soil surface and zones beneath.
Loss by uptake by roots and
movement to the soil surface
and the zones beneath.

Addition by subsurface
application and by trans-
port from the soil surface
and zones beneath.
Loss by decomposition by
chemical and biological
means, by uptake by roots,
and by transport to the
soil surface and the zones
beneath.
Retention by the soil.

Unsaturated
zone below
root depth

Addition by movement from the
zones above and beneath.
Loss by movement into the zones
above and beneath.

Addition by transport from
the zones above and
beneath.
Loss by decomposition by
chemical and
biological means and by
transport into the zones
above and beneath.
Retention by the soil.

Saturated zone
(groundwater)

Addition by movement from the
zones above and by lateral and
vertical movement within the
saturated zone.
Loss by movement into the zones
above and by lateral and vertical
movement within the saturated
zone.

Addition by transport
from the zones above and
by lateral and vertical
transport in groundwater.
Loss by transport into the
zones above, by lateral and
and vertical transport
within the saturated zone,
by discharge to bodies of
surface water, and by
decomposition by chemical
and biological means.
Retention by the soil.

Table 3. Principal Agriculture-Related Substances of Concern in Groundwater Quality, Their Effects, and Preventive and Corrective Measures. [CAST, 1985].

Substance	Effects	Preventive and Corrective Measures
Soluble salts	Decreased crop growth; laxative effect of high sulfate concentration.	Flush excess salts out of soil; remove the salts from the drinking water or substitute another source.
Nitrate	Infant methemoglobinemia.	Remove the nitrate or substitute another source for drinking; deepen the well and case it properly to avoid contamination from shallow groundwater; avoid accumulation of excesses; modify management to reduce excesses.
Bacteria	Water-borne diseases.	Boil the water or substitute another source for drinking; deepen the well and case it properly to avoid contamination from shallow groundwater; avoid contamination.
Pesticides	Toxicity of excesses.	Remove the pesticides from the water or substitute another source for drinking; deepen the well and case it properly to avoid contamination from shallow groundwater; avoid accumulation of excesses; modify management to reduce excesses.

Table 4. Glossary of Terms Associated With Contamination of Groundwater.

GLOSSARY*

- Point Source** - Where a chemical directly enters groundwater through a discrete pathway such as by back-siphoning, leaking through an abandoned well, or through sinkholes in karst soils.
- Non-Point Source** - Where a chemical enters the groundwater by leaching through soil over a wide area. The chemical is usually transported with rainfall or irrigation.
- Cation Exchange Capacity** - The capacity of soils to adsorb cationic compounds such as plant nutrients and some pesticides.
- Sorption** - This term encompasses adsorption, desorption, ion exchange, and partitioning processes.
- Adsorption (Partitioning)** - The process by which substances penetrate into the interior of soil materials or roots. When a systemic pesticide is taken into a root, it is by the process of absorption.
- Desorption** - The opposite of absorption.
- Adsorption** - The process by which substances (pesticides) adhere to the surface of soil particles.
- Half-life** - The period of time it takes for one-half of a pesticide in the soil to microbially degrade.
- Evapotranspiration** - (ET) A combination of evaporation from the soil (E) and transpiration from the plant surface (T).
- Water holding capacity** - The amount of water held by the soil when saturated: usually measured in inches.

* After Farm Chemicals, 1989.

Table 5. Everyone Contributes To Groundwater Contamination. [After Farm Chemicals, 1989].

Activity	Estimated Sites ¹	Contaminants frequently cited as result of activity
Waster disposal:		
Septic systems	22 million	Bacteria, viruses, nitrate, phosphate, chloride, and organic compounds such as trichloroethylene.
Landfills (active)	16,400	Dissolved solids, iron, manganese, trace metals, acids, organic compounds, and pesticides.
Surface impoundments	191,800	Brines, acidic mine wastes, feedlot wastes, trace metals, and organic compounds.
Injection wells	280,800	Dissolved solids, bacteria, sodium, chloride, nitrate, phosphate, organic compounds, pesticides, and acids.
Land application of wastes	19,000 land application units	Bacteria, nitrate, phosphate, trace metals, and organic compounds.
Storage and handling of materials:		
Underground storage tanks	2.4-4.8 million	Benzene, toluene, xylene, and petroleum products.
Above-ground storage tanks	Unknown	Organic compounds, acids, metals and petroleum products.
Material handling and transfers	10,000-16,000 spills per year.	Petroleum products, aluminum, iron, and trace metals.
Mining activities:		
Mining and spoil disposal - coal mines	15,000 active 67,000 inactive	Acids, iron, manganese, sulfate, uranium, thorium, radium, molybdenum, selenium, and trace metals.

Oil and gas activities:		
Wells	550,000 production; 1.2 million abandoned	Brines.
Agricultural activities:		
Fertilizer and pesticide applications	363 million acres ²	Nitrate, phosphate, and pesticides.
Irrigation practices	376,000 wells 49 million acres irrigated ³	Dissolved solids, nitrate, phosphate, and pesticides.
Animal feedlots	1,900	Nitrate, phosphate, and bacteria.
Urban activities:		
Runoff	47.3 million acres urban land ⁴	Bacteria, hydrocarbons, dissolved solids, lead, cadmium, and trace metals.
Deicing chemical and use	Not reported	Sodium chloride, ferric ferrocyanide, sodium ferrocyanide, phosphate, and chromate.
Other:		
Saline intrusion or upconing.	Not reported	Dissolved solids and brine.

¹ Estimated number of sites from U.S. Environmental Agency (1987) unless otherwise indicated.

² U.S. Bureau of the Census, 1984, p. 666, 1981 data.

³ U.S. Bureau of the Census, 1984, p. 639, 1982 data.

⁴ U.S. Bureau of the Census, 1984, p. 195, 1980 data.

Source: Adapted from 1986 National Water Summary, 1988, page 140, Data compiled from "State Summaries of Ground-Water Quality," part of the 1986 National Water Summary unless otherwise indicated.

Table 6. Half-Life and Sorption Coefficient of Several Common Chemicals
[after Farm Chemicals, 1989].

The chart below lists the sorption coefficient and half-life of a number of commonly used ag chemicals. The Koc could be considered an index for chemical mobility, but one should take into account the chemical's half-life. For instance, the top two chemicals have relatively low Koc, which might imply they have the potential to leach. However, they have a short half-life so generally do not last long enough in the environment to reach groundwater supplies.

Product common name	Half-life (days) T _{1/2}	Sorption Coefficient K _{oc}
Dicamba	14	2
Oxamyl	7	9
Metalaxyl	7	16
Picloram	90	16
Chlorimuron	50	20
Imazaquin	60	20
1,3-dichloropropene	10	26
Methomyl	8	28
Carbofuran	30	29
Aldicarb	30	30
Naptalam	7	32
Captan	3	33
Bentazon	10	35
Terbacil	90	41
Diphenamid	32	67
Fonofos	45	68
Bromacil	90	72
Diazinon	30	85
Acephate	3	100
Clomazone	30	100
Ethoprop	50	120
Oryzalin	70	138
Simazine	75	138
Acifluorfen	30	139
Atrazine	60	163
Chlorambem	14	190
Alachlor	10	190
Vernolate	12	200
Metolachlor	20	201
Carbaryl	7	229
EPTC	30	280
Norflurazon	45	248
Diuron	100	400
Sulprofos	14	550
Linuron	60	863
Phorate	90	1000

Product common name	Half-life (days) *T $\frac{1}{2}$	Sorption Coefficient ** K oc
Lindane	90	1100
Chlorothaionil	20	1380
Chloroneb	180	1653
Malathion	1	1800
Benomyl	200	2100
Chlorpyrifos	30	6070
Diflubenzuron	10	6790
Glyphosate	30	10,000
Parathion	14	10,650
Diclofop-methyl	10	48,500
Fenvalerate	50	100,000
Paraquat	3600	100,000
Ethalfuralin	60	471,000
DDT***	365+	243,000

* Half-life is a period of time it takes for one-half of a pesticide in the soil at a given time to microbially degrade. Half-life can vary due to soil microbial populations, soil moisture, soil temperatures, and farming practices. These numbers represent a typical value taken from scientific literature.

** The larger the K oc, the more strongly the pesticide is held in soil organic matter and the less likely it will leach. The K oc value represents the sorption of the pesticide on the soil normalized by the organic matter (organic carbon) to provide a single representation of a particular chemical for all soils. For this reason, the uncertainty could be plus or minus 2X.

*** DDT is no longer registered but is included here as a reference.

Source: SCS Water Quality Workshop Manual, October, 1988.

These numbers are useful in comparing relative differences and should not be construed as absolute values.

Table 7. Factors Influencing Changes in Pesticide Use Patterns
[after Cal, 1989].

Genetic

- * crop species
- * variety
- * pest resistance
- * chemical resistant
pests

Environmental

- * location
- * climate
- * year to year changes
- * soil
- * water
- * pest populations &
inoculum levels
- * beneficial organisms

Agronomic

- * cropping pattern
- * planting date
- * irrigation methods
- * field selection
- * tillage

Economic/Policy

- * management system on farm
 - * consumer demand/market structure
 - * relative costs of control practices
 - * regulations & farm programs
 - * farmer beliefs and attitudes
-

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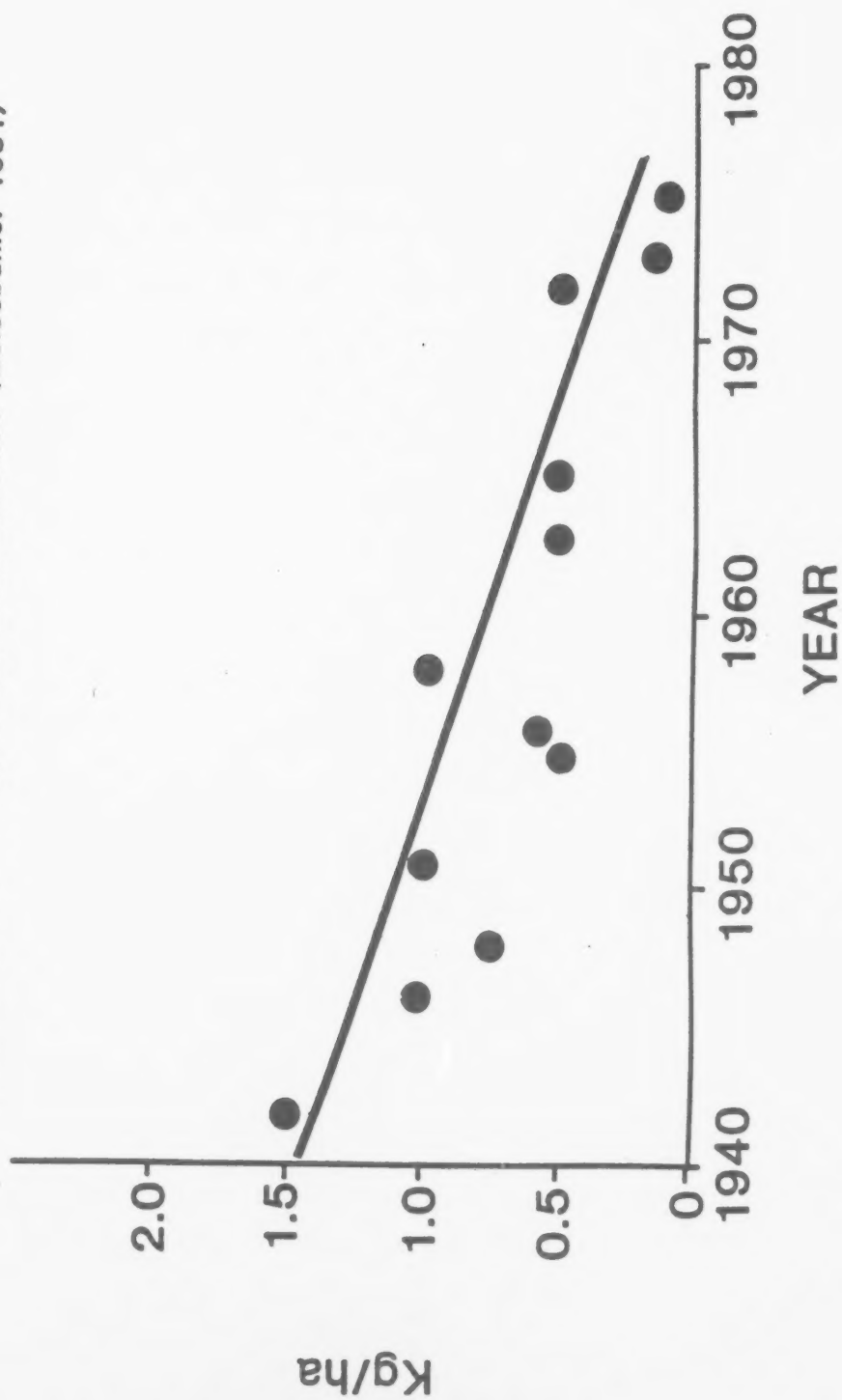
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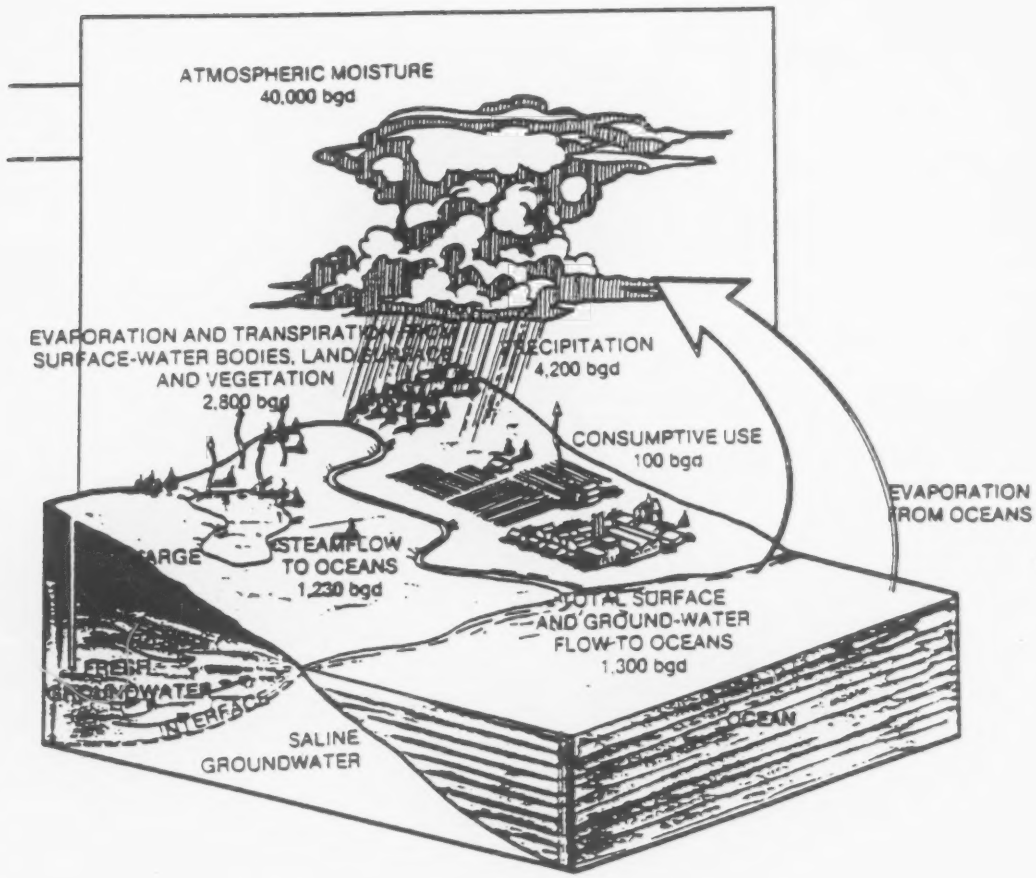
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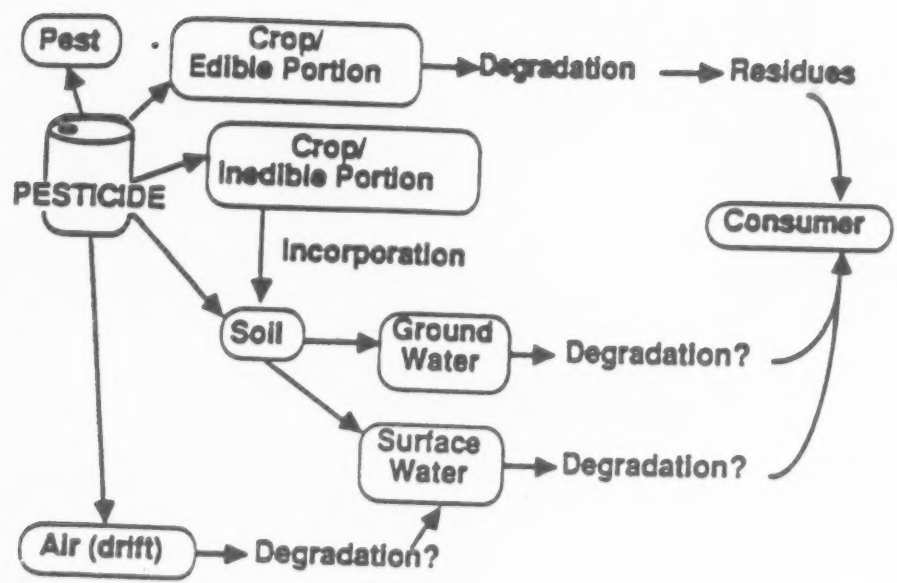
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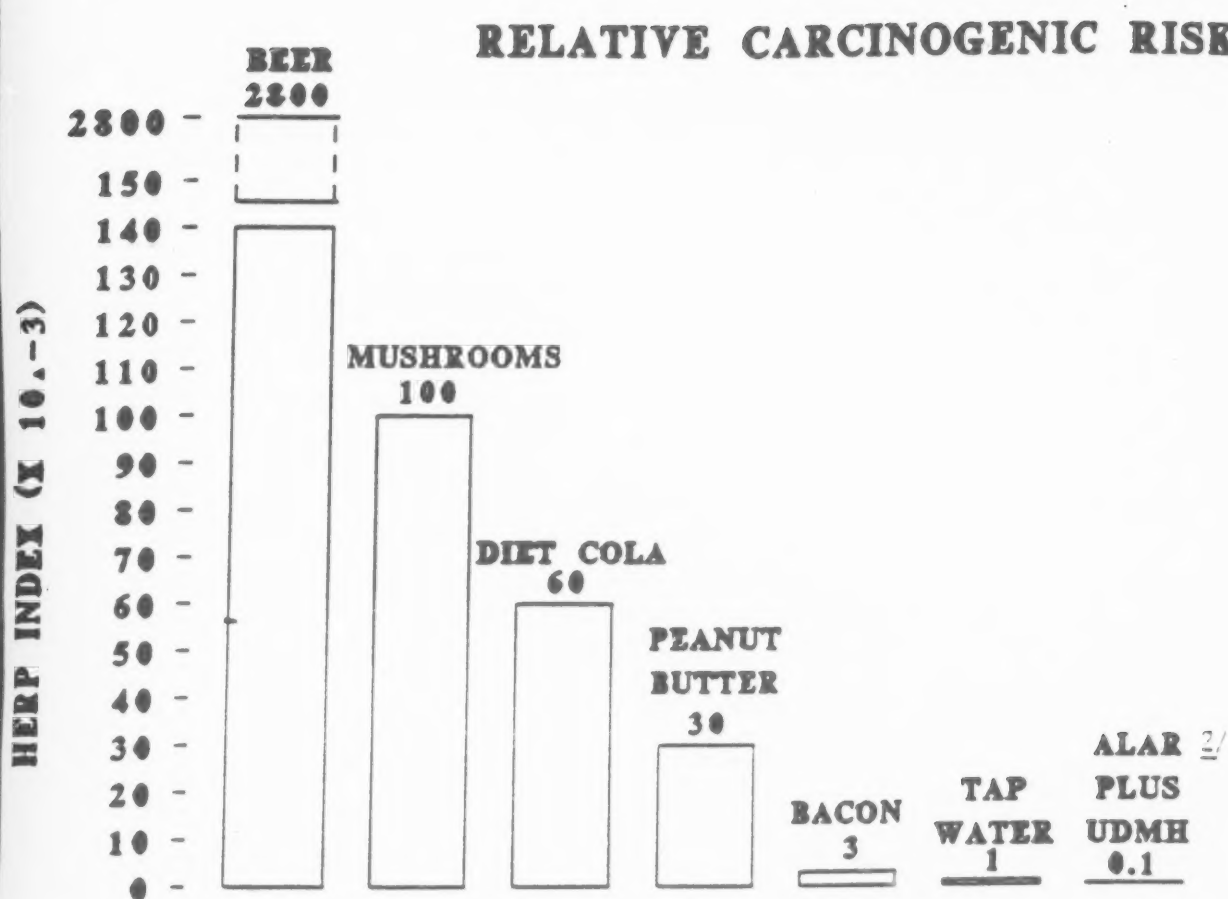
1. The increasing efficacy of pesticide technology.
2. The Hydrologic Cycle [bgd = billion gallons per day].
3. Pesticide distribution pathways.
4. Ames Herp Index.
5. Pesticide hazard rating system.
6. Public perception of pesticide hazards.

Evolution in rate of application of insecticides (Geissbuhler 1981)





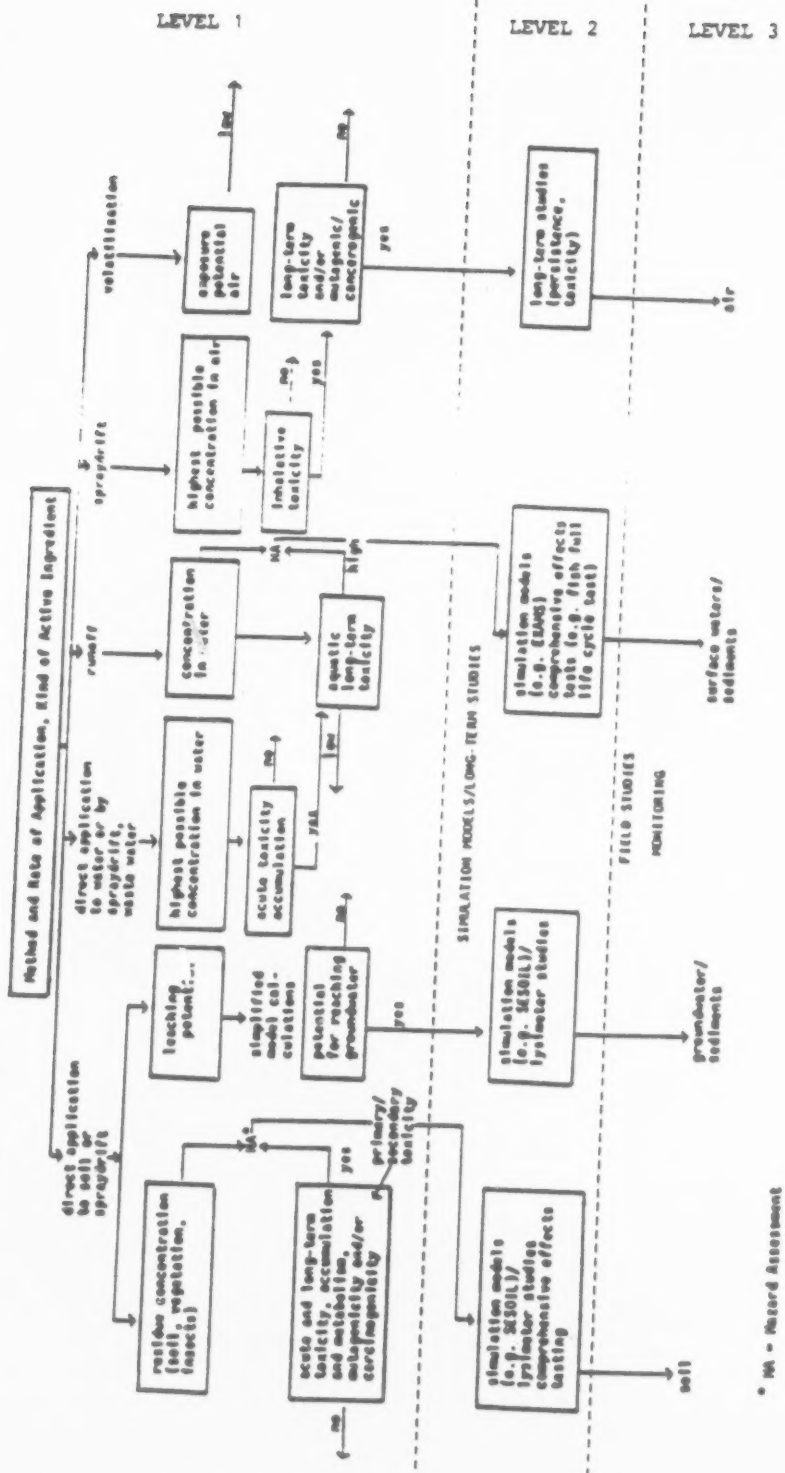




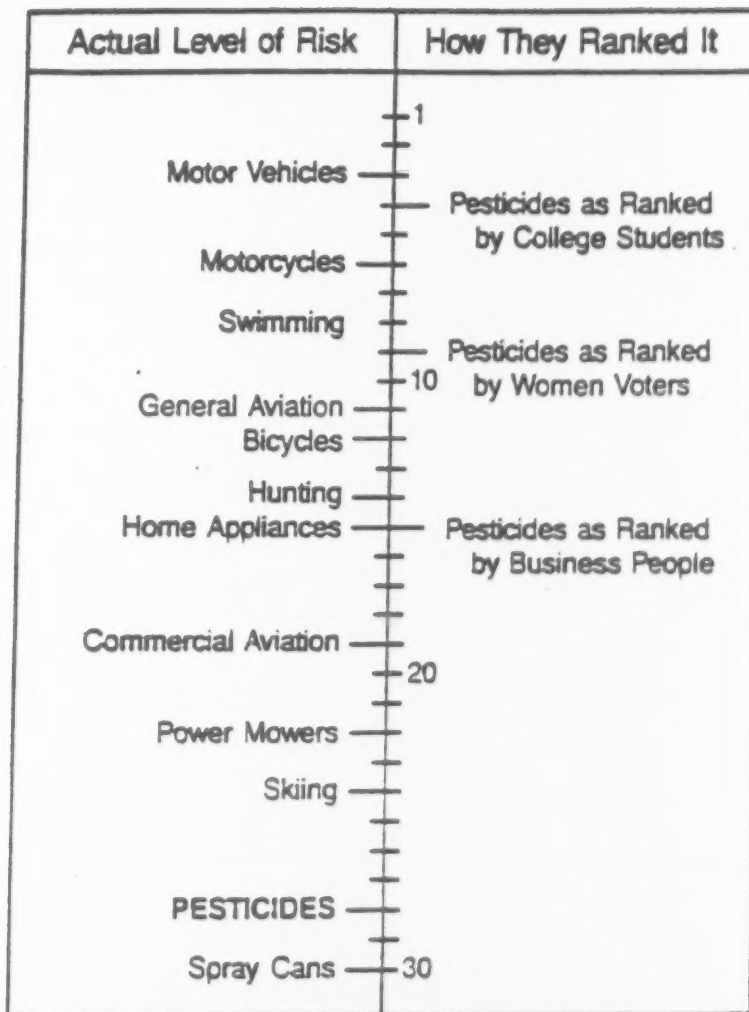
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ASSESSMENT SCHEME FOR PESTICIDES



* HA = Hazard Assessment



How Risky Are Pesticides?

**INTEGRATED PEST MANAGEMENT:
POTENTIAL FOR REDUCING AGRICHEMICAL CONTAMINATION OF
GROUNDWATER**

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ABSTRACT

The impact of pesticide use on the environment is a complex issue. Contamination of groundwater with pesticides is a potentially serious environmental issue which is not well understood. Technologies intended to lower pesticide use will limit the overall amount of pesticides introduced into the environment.

Integrated pest management (IPM) is the systems approach to reduce pest damage to tolerable levels using biological controls, cultural controls, genetically resistant hosts, and when appropriate chemical controls, especially those which are selective and do not contribute to environmental contamination including groundwater. It requires the interaction of individuals from all of the pest management disciplines, plant and animal sciences, social and behavioral sciences, mathematics and systems science, and farmers and extension agents. Basic elements of an IPM program include research and extension to produce a body of information on farming practices and pest biology, a program for monitoring pests, natural enemies and crop status throughout the season, control action thresholds, IPM tactics for pest control, and crop consultants to apply the program.

Until recently, there were few studies focussed upon the implementation process, including incentives for and constraints to adoption. Where empirical estimates of IPM impact have been made, most studies have shown an advantage of IPM over conventional control in terms of increased production, greater net cash return, improved risk management, and lessened environmental impact through reduced pesticide use. The potential for reduced pesticide use has been the most important stimulus to the development and promotion of IPM by government agencies and educational institutions. More recently, the economic advantages of IPM have been stressed because of its significance to growers. User education is a key element in successful implementation of complex technologies such as IPM. When comprehensive and well organized programs have been attempted such as the federally sponsored

Extension IPM Pilot Projects, the level of adoption has been high and the amount of pesticide use lower. Such programs have helped to accelerate the development of the private pest management industry which provides information services to growers on crop production and pesticide use.

IPM programs are far from being universally adopted, even when available and validated. Important constraints to IPM use have been categorized as technical, financial, educational, institutional and social. Some of these constraints could be addressed through better organized and funded research, teaching and extension efforts, which could require reorganization of some of the basic structure of both the Agricultural Experiment Stations and Cooperative Extension as well as appropriate divisions of the USDA. Better analysis of the impact of regulations and farm policy on pesticide use should be instituted so that such government efforts do not actually increase pesticide use. Private sector incentives for developing and marketing biological controls and biological pesticides should be made. Development of the private pest management industry should be encouraged, possibly linking the issue to stronger controls on the purchase and use of pesticides.

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PESTICIDE USE IN THE UNITED STATES

Pests including insects, mites, weeds, disease-causing organisms and vertebrates lower quality and yield of agricultural products.

Before World War II, farmers relied heavily on non-chemical pest control methods such as crop rotation, tillage, bait trapping and hand-removal of pests. Weeds were removed by hand-hoeing and tillage; chemical herbicides were seldom applied. Available pesticidal materials contained metals such as copper, lead, antimony and arsenic, and botanical compounds such as nicotine and pyrethrum. These materials were toxic and expensive to produce in quantity, therefore their availability was limited. Equipment for their application was relatively unsophisticated or lacking. Overall pesticide use was low relative to contemporary levels. Also during this period, an awareness of the effectiveness of biological control was developing. This awareness was initiated following the successful introduction of the Vedalia beetle from Australia to California in 1890 to control a serious pest of citrus, the cottony cushion scale (Huffaker, 1971).

The development of synthetic pest control chemicals during World War II, in combination with improvements in application

technology, increased the potential for pest control dramatically. Pest control researchers overwhelmingly embraced and perfected the technology. Governmental policies including tax incentives made the production and use of pesticides attractive to businesses and farmers. Extension agents and pesticide salesmen promoted pesticide use. In effect, pesticide development, production and use became institutionalized, and farmers became increasingly dependent upon them. As a result, pesticide use in the United States increased 19,000 fold from 1940 to 1976 (Willey, 1977). Pesticide use has stabilized since that time, and has actually decreased about 14% overall since 1982 (United States Department of Agriculture, 1988). In contrast, pesticide use on certain crops and pests has increased. For example, in 1985, 95% of corn and soybean acreage was treated with herbicides compared to 40% in 1970 (United States Environmental Protection Agency, 1986). Most of this increase is due to the widespread use of no till practices in the midwest. It is interesting to note that about 90% of all herbicides and insecticides are applied to 4 crops: corn, cotton, soybeans and wheat (United States Department of Agriculture, 1986).

PROBLEMS WITH PESTICIDE USE

Pest resistance. Pest resistance to a chemical can develop rapidly because the life cycle of the pest is relatively short. Many

species of insects and mites complete 3 or more reproductive cycles (ie., generations) in one growing season. In a pest population, there are always some individuals which will be genetically resistant to the pesticides. Even when a high percentage of the population is killed, these few individuals will survive and reproduce, passing their genes for resistance into the succeeding generation. Thus, a pest population develops which can only be controlled by higher dosages of the chemical. Eventually, the pesticide being applied can become ineffective against the pest. Thus, most pesticides have a limited effective life. As of 1986, resistance had been reported in at least 447 species of insects and mites, 100 species of plant pathogens, 48 species of weeds, 5 species of rodents, and 2 species of nematodes (Georgioui, 1986).

Secondary Pest Outbreaks. Many plant-feeding insects do not significantly damage agricultural crops because they are kept under natural control by predators and parasites. However, these natural control agents can be inadvertently disrupted by chemical applications which target the bonafide pest species. This situation can results in the emergence of new pest species, called secondary pests, which have been released from natural control. For example, it is widely believed that spider mites have emerged as a serious agricultural and forest pest since 1946 because their predators have been reduced by chemical sprays for primary pests.

Effect upon non-target organisms. Pesticides generally kill a broad spectrum of plant-associated organisms, only a fraction of which are the target pests. Pesticide-induced losses of commercial honeybees are between \$20 and \$50 million annually, across the nation (Dr. E. C. Mussen, personal communication, April 25, 1989). Other beneficial organisms which are affected by pesticide applications include plant-feeding insects which are a food source for predator populations when the pests are not abundant, and those organisms which function in decomposition and mineral recycling in the soil. In addition, pesticides may have phytotoxic effects on crops resulting in reduced yields or quality.

Human exposure. There are several ways in which people may come in contact with pesticides, but the most common are during the application process and when entering recently treated areas. However, when proper protective clothing and equipment are worn during the mixing and application of pesticides, exposure will be very low. Pesticide label guidelines regarding reentry of treated fields and harvest intervals are intended to protect agricultural workers and consumers.

The non-agricultural public may also be exposed to small doses of pesticides if they live near treated areas (through air-drift, contaminated drinking water, etc.), eat contaminated food, or touch recently treated livestock, foliage or stored food products.

Other environmental hazards. The impact of pesticide use on the environment is a complex issue. Some pesticides are extremely slow to break down due to natural processes and lose their toxicity very slowly. The chlorinated hydrocarbon insecticides, including DDT, chlordane and others widely used in the U.S. throughout the 1950's and 1960's, are among these persistent chemicals. Persistent soluble pesticides may filter into the soil and be carried away by irrigation or rain water into streams where they enter the food chain via consumption by microorganisms, invertebrates and fish. As these are consumed, in turn, by higher organisms, the pesticide is concentrated and carried to fish, wildlife, livestock and humans. DDT was banned in the U.S. in 1972 after the highly publicized discovery that it caused mortality in wild bird populations by causing them to produce thin-shelled eggs.

PESTICIDES AND GROUNDWATER

Potential contamination of ground water with pesticides has become an environmental issue which is potentially serious, but is not well understood.

Groundwater is the source of water for wells and springs. It is found underground, within cracks of bedrock or filling the spaces between particles of soil and rocks. The groundwater layer in which all available spaces are filled with water is called the saturated zone. The dividing line between the saturated zone and overlying unsaturated rock or sediments is called the water table. The geologic formation through which groundwater flows is called an aquifer.

Groundwater is important because it supplies drinking water to approximately half of the United States population; more than 90 percent of rural residents obtain their water from groundwater sources. There are good reasons for widespread dependence on groundwater. It is usually of high quality and can be used without costly treatment or purification. It is often immediately adjacent to the use site, and storage facilities are not needed. The water is simply pumped as needed.

Water entering the soil from rainfall or irrigation gradually percolates downward to become groundwater if it is not first taken up by plants, evaporated into the atmosphere, held within soil pores

or transported elsewhere as runoff. This percolating water passes downward through the root zone and unsaturated zone until it reaches the water table. Programs for protecting groundwater must focus on the environment during the first phase of the recharge process since conditions in the upper levels control both the quantity and quality of water reaching the saturated zone. Water is far easier and less expensive to manage at the surface; after it reaches the saturated zone protection or clean-up are extremely difficult.

Once underground, water moves slowly through irregular spaces within rock fractures or between particles of sand, gravel or clay. Generally, groundwater moves only a few feet per month or even per year. In some cases, however, it may move much more rapidly.

The quality of recharge received by aquifers depends on their depth from the ground surface, the geology of the overlying materials, and on climate, land uses and water and chemical management practices in the recharge areas.

Pesticides. Pesticides have become an integral component of agricultural systems throughout the world. In its current state of technological development, United States agriculture has become dependent upon pesticides to maintain predictable, cost efficient production. However, off-site costs including environmental contamination and food safety risks are not borne solely by

agriculture. Therefore, such societal costs are rarely considered when determining agricultural production costs and efficiencies.

Varying amounts of pesticides have been found in groundwater in the United States. These include insecticides, herbicides, fungicides and nematicides. A total of 67 pesticides have been detected in a total of 33 states (Williams et al., 1988). Many of these were detected in only a single well and at levels of one part per billion or less. At least 17 pesticides have been found in groundwater at levels which exceed the "Health Advisory" level set by the United States Environmental Protection Agency. Health advisories are a set of non-enforceable health guidelines used to help state and local officials evaluate the health significance of chemicals found in groundwater.

Pesticides in groundwater have generally been found at very low levels. Human health concerns about pesticides in groundwater are focussed on long term or chronic effects rather than the more clearly understood acute effects of high dosage pesticide exposure (Cantor et al., 1988). Although conclusive evidence that long term exposure to low levels of pesticides in groundwater is harmful has not been established, there is a public perception of risk concerning pesticides in drinking water (Pratt, 1985; Anderson and Balogh, n.d.).

Agricultural producers living in rural areas share the public's concern over chemical hazards to their water supply. They would benefit from a rational system of managing pesticides for

groundwater protection which would reassure the public that the environment is being protected. Our challenge is to mitigate the hazards of pesticide use or to develop and implement nonchemical management strategies while maintaining efficient agricultural production.

Sources. Two general sources of pesticide contamination of groundwater can be described: point sources and non-point sources. Point sources are single points of entry into the groundwater, for example, contamination through a well or an industrial waste disposal site which has a direct opening to an aquifer. Non-point sources are from diffuse and generally legal chemical applications. Application may be over an extensive area, and transport is by subsurface percolation; entrance to groundwater is from many dispersed points and it is usually intermittent; precise management of conditions at the exact point of origin is difficult and the pollutants are usually not traceable to their exact source; the magnitude of contamination is related to variable climatic processes (Daniel and Schneider, 1979).

Recent studies suggest that agriculture makes a significant contribution to water contamination and sedimentation (Canter, 1987; Leonard, 1988). The potential for groundwater contamination by pesticides depends upon the properties of the pesticide used and the method of application as well as such factors as soil characteristics, depth of the water table, amount of post-application

irrigation, and precipitation (Porter and Stimmann, 1988). Prevention of groundwater contamination by using improved pesticide application practices and by implementing IPM and other alternative pest management approaches intended to reduce pesticide use has the potential to be a cost effective measure for protecting our groundwater resources.

The fate and degree of pesticides in the soil and groundwater environments is influenced by a number of physical factors that are measurable and at least somewhat predictable. Pesticides reach the soil surface by direct application, movement through air, from treated plants, by lateral transport from adjacent areas, by precipitation and by upward transport. Pesticides reach the root zone and below (unsaturated soil) by transport from the soil surface and from zones below. Pesticides reach the saturated zone by downward and lateral water movement. Pesticides are lost to each of these soil zones by volatilization, runoff, leaching to adjacent zones and by chemical or biological decomposition. Once below the root zone, biological decomposition is greatly reduced, other decomposition processes predominate, and pesticide decomposition is slowed.

The potential for transport of pesticides from the root zone to groundwater is determined by a complex interaction of chemical, soil, climatic and management factors (Anderson and Balogh, n.d.). Most important factors influencing the rate of pesticide movement below

the root zone are site specific and related to subsurface losses of pesticides. Included among these are depth to groundwater, geologic substrate and cropping and tillage systems (Anderson and Balogh, n.d.). Timing of precipitation or irrigation relative to pesticide application, occurrence of preferential flow paths, pesticide handling and disposal practices may have profound effects on pesticide transport (Anderson and Balogh, n.d.). Chemical and physical properties of pesticides also influence how they will move below the root zone, and these attributes are not site specific.

Reducing contamination. Careful management of the type, amount and application method of pesticides will help to limit the pesticides reaching groundwater. Federal and state pesticide registration procedures are being modified to require consideration of the pesticide's potential for reaching and contaminating groundwater before specific pesticides are registered for use. Pesticides with significant potential for reaching groundwater can be selectively registered to minimize or eliminate their use in sensitive environments.

Pesticides registered for use against pests living in, on or near the soil should be carefully scrutinized for groundwater contamination potential. When registered for such uses, restrictions should be imposed which will require special handling, or training for applicators. When necessary, use on vulnerable soils could be prohibited. Application techniques for pesticides with high potential

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for reaching groundwater should be restricted to methods which will minimize potential for contamination.

Integrated Pest Management (IPM) has resulted in significant decrease of pesticide use in several crops. These pesticide use reductions occur because IPM practitioners are trained to pay careful attention to the actual need for the pesticide, as well as its timing and application. Reducing groundwater pesticide contamination is a potential benefit of IPM programs. Crop rotation, pest monitoring, use of alternate chemicals or non-chemical controls, crop condition, soils, irrigation practices, weather and market conditions must all be considered to achieve the overall goal of minimizing pesticide use in agriculture.

IPM DEFINITIONS

A variety of definitions exist for the term Integrated Pest Management. The U.N. Food and Agriculture Organization's (FAO) Panel of Experts on Integrated Pest Control (1967) defined IPM as:

a pest management system that, in the context of the associated environment and the population dynamics of the pest species, utilizes all suitable techniques and methods in as compatible a manner as possible and maintains the pest populations at levels below those causing economic injury.

The Council on Environmental Quality (CEQ) in its publication *Integrated Pest Management* (1972) defined IPM as:

an approach that employs a combination of techniques to control the wide variety of potential pests that may threaten crops. It involves maximum reliance on natural pest population controls, along with a combination of techniques that may contribute to suppression--cultural methods, pest-specific diseases, resistant crop varieties, sterile insects, attractants, augmentation of parasites or predators, or chemical pesticides as needed.

In urging the adoption of IPM, President Carter defined it in his 1979 Environmental Message as follows:

IPM uses a system approach to reduce pest damage to tolerable levels through a variety of techniques, including natural predators and parasites, genetically resistant hosts, environmental modifications and, when necessary and appropriate, chemical pesticides. IPM strategies generally rely first upon biological defenses against pests before chemically altering the environment.

The theory of IPM as provided in these definitions are relevant today as agriculture faces the need to move away from reliance upon pesticides. It is ironic, though that the theory has not been widely translated into practice.

The word *management* implies acceptance of pests as inherent components of the agricultural system. The IPM approach is to apply

controls to suppress pest populations when necessary to reduce crop damage, rather than to eliminate the pest. The term pest encompasses all organisms which are damaging to crop production. These include insects, mites, disease-producing organisms, weeds, nematodes and vertebrates.

The word *integrated* is used because it implies combining all appropriate methods from a broad range of scientific disciplines into a single system. These methods must be compatible with each other and with the total crop production and marketing systems. The goal of the IPM system is to optimize pest control within the overall constraints of these other systems.

The land grant college system has evolved strong disciplinary departments (e.g., plant sciences, entomology, plant pathology, economics, systems science, etc.). These departmental units are typically not well linked and are not encouraged to interact with one another in interdisciplinary research. Successful development and application of IPM programs require interdisciplinary interaction because of its systematic treatment of all components of agricultural production.

BASIC ELEMENTS OF IPM

A comprehensive Integrated Pest Management program for an agricultural system is comprised of these basic elements: 1)

dedicated research and extension personnel to produce a body of timely information concerning farming practices, pest biology and pest management tactics to formulate the program, 2) a program to monitor pests and natural enemy population levels and the state of the crop throughout the season, 3) control action thresholds --levels of pest abundance at which some control action must be taken to protect the crop from unacceptable economic loss, 4) IPM tactics which involve a spectrum of agents and materials used to suppress pest populations, 5) crop consultants to apply the program in the field, and 6) willing and cooperative growers.

IPM TACTICS

Biological controls. Biological control is the augmentation, conservation and importation of natural enemies--predators, parasites and disease pathogens--to reduce a pest population. This may involve either the introduction of a natural enemy or the augmentation of one which already exists in the crop ecosystem. Biological control is generally considered to be the cornerstone of any IPM program. Mass culture and release of predatory lacewings, various species of parasitic wasps, and insect pathogens such as *Bacillus thuringiensis*, have been effective in insect pest management programs. The release of certain species of plant-feeding insects have been successful in controlling some rangeland weed pests, such as St. Johnswort (*Hypericum perforatum*) (Crafts and Robbins, 1962). The application of disease-causing fungal spores has been promising in the control of weeds such as northern jointvetch (Templeton, et al., 1976). Biological control has the advantage of being generally safe to non-target organisms. Classical biological control--the release of an imported natural enemy to control a pest species--when successfully established has more permanence in the environment than do chemical tactics. However, disease agents such as fungal spores and *Bacillus*, and mass reared

natural enemies used in augmentative releases, generally do not persist and must be re-released periodically.

Cultural controls. Such controls include a broad range of production practices which render the crop environment less favorable for the pest. Tillage and water management are effective cultural controls in the management of weeds. Tillage also may bury weed seeds. Further, increases in mortality in many insects which overwinter in the soil are also likely to result from tillage practices. The destruction of crop residues is important in the management of many pests, such as navel orangeworm in almond, late blight of potato, stem rot of rice and pink bollworm and boll weevil in cotton, for which there are compulsory plow-down dates in several regions. Manipulating planting and harvesting dates permit breaks in the development of pest populations in regions where pests could develop throughout the year. Crop rotation can also be used to break the life cycles of many species. Applying fertilizer with the seed of annual crops or through drip irrigation systems can provide a measure of weed control, especially in contrast to broadcast application of fertilizers which stimulates weed growth. Cultural controls have been used historically to manage many pests, but were often abandoned in favor of pesticides which were less labor intensive.

Genetic controls. This tactic includes the traditional breeding of plant varieties resistant to pests, a most effective and economical

means of controlling plant disease, nematodes, and insect pest deprecations. More recently, genetic engineering has been heralded as a more efficient mechanism for effecting pest resistance. This involves the insertion of genetic material governing various plant characteristics into plant tissue. At present, however, no commercial product derived from this technology is available for use. Genetic control can also be specifically applied to pests; an example is the sterile male release technique which has been undertaken to control the screwworm in cattle, pink bollworm in cotton, and the Mediterranean fruit fly. Males are bred and sterilized with radiation, then released in large numbers. Females which mate with these males then lay sterile eggs.

Chemical Controls. Chemical controls usually produce quick results and require little understanding of the pest biology or the crop ecosystem. However, timing an application to vulnerable stages of the pest and thorough spray coverage frequently affects the efficacy of the application. Mature stages of scale insects and weeds and many species of stink bugs are nearly impervious to many chemicals. Early immature stages of insects and weeds generally require less toxic materials in smaller doses than later stages for control.

In an IPM program, pesticides are only used after systematic monitoring of pest populations and consideration of natural control factors, not according to a predetermined schedule. When chemical

tactics are deemed necessary, the choice of a selective pesticide which kills only the target species is desirable because it is the least disruptive to the crop ecosystem. Examples include some acaricides for spider mite control which do not affect beneficial predatory mites. Most older pesticides are broad-spectrum, however, and proven nonchemical alternatives do not exist for many pests. Herbicide use has more than doubled since 1970, currently accounting for 65% of all pesticides used in the United States (National Research Council, 1989). Concern for soil erosion manifested in such practices as conservation tillage has, in part, stimulated this reliance. Herbicides such as glyphosate are non-selective and kill all plants before planting the crop. Selective herbicides kill a general group of plants, such as broad-leaves or grasses. The development of tolerance levels and control action thresholds for weeds, and viable alternatives to herbicides for weed control is a major challenge for current IPM research.

Fungicides are commonly applied to plants to prevent leaf blights, rusts, smuts, mildew, and other fungal diseases. Repeated applications usually are required to protect new growth. In recent years, the scheduling of fungicide applications on the basis of weather monitoring, in lieu of a predetermined schedule, has resulted in a substantial reduction in number of applications where applied. An example in wide use is "Blitecast," which was developed

at Pennsylvania State University for the control of late blight on potato (Krause and Massie, 1975).

Behavioral chemicals. Pheromones are highly specific chemicals released by insects to affect the behavior of members of their own species. Chemical analogs of those pheromones released by females to attract males are frequently used in IPM programs. In fact, over 300 pheromones have been isolated and synthesized to date (Arn et al., 1986). Placed in specifically designed traps, these powerful attractants have become an integral part of insect monitoring systems. The direct use of pheromones as control agents has met with some success. The pheromone is distributed over the field in dispensers. Slow volatilization of the pheromone from the dispensers confuses the males and inhibits their locating of females thus disrupting mating. This technique, known as male confusion, is used to control oriental fruit moth in Australia and recently on over 6000 acres of peaches in California (Weakley et al., 1987). It is also being used to control tomato pinworm and to some extent the pink bollworm in the U.S. and Mexico (Jimenez et al., 1988).

Predictive models in IPM. Current pest simulation models developed by IPM researchers are a framework for integrating information from the various biological disciplines, meteorology, and the field monitoring of pest populations. The models, which predict aspects of plant growth and pest populations levels, can be useful in the decision-making process. IPM programs have pioneered many

applications for computer technology in agriculture and use electronic instruments for field data gathering (Zalom, 1989). These powerful tools improve data acquisition and delivery systems for pest management information.

DEGREE OF CURRENT IPM USE

Many studies have considered the adoption of agricultural innovations (Rogers, 1983), but few reviews have been made of IPM implementation. Until recently there were also few studies focussed on the IPM implementation process including incentives for and constraints to adoption. As early as 1964, concerns were voiced by IPM researchers (van den Bosch, 1964) about the slow rate of integrated control, and particularly biological control, adoption by farmers. Some authors (c.f. Lincoln and Parencia, 1977; Norton, 1982; Pimentel, 1982) have acknowledged the problem and have recognized that the complexity of IPM will delay its adoption. Others have undertaken more detailed studies focussing upon the economic, social, organizational, and institutional constraints. These will be discussed in more detail later.

Grower focus. Because IPM is so intimately tied to crop production, it is difficult to make generalizations about adoption beyond specific crops. Further, the degree to which IPM is implemented on a specific crop can vary as growers may modify the

innovation to fit their requirements, a process termed adaptive implementation (Berman, 1980) or reinvention (Rogers and Shoemaker, 1971), or may use only selected IPM management techniques.

An example of adoption versus adaption was presented by Grieshop et al. (1988) in a study of implementation of IPM monitoring techniques in California processing tomatoes. They found that over the 5 year period since the techniques were first available, 26 percent of all growers had adopted the IPM techniques while 31 percent had adapted (or reinvented) the techniques. In this case, the degree to which the program was modified had little effect on results, but better fit the growers' practices. Mixed levels of adoption of selected practices among several available in an IPM cropping system was noted by Zalom et al. (1987) in California almonds where some cultural controls (e.g. timely pickup of nuts from ground, winter sanitation, harvest before pest flight) for the key pest, navel orangeworm, were broadly adopted. Other techniques (e.g. artificial drying of harvested nuts) were not (Table 2). In the same study, monitoring techniques for spider mites and navel orangeworm were used by at least 50% of the growers, while monitoring techniques for San Jose scale and oriental fruit moth were used by less than 25% of the growers, roughly corresponding to the perception of importance of the pests by the growers.

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In 1984, a national evaluation of extension IPM programs was undertaken and coordinated by the Virginia Cooperative Extension Service (Rajotte et al., 1987). Fourteen states undertook case history studies of specific IPM programs. Of these, 10 of the studies identified the level of IPM adoption by growers. Levels of adoption in excess of 50 percent were noted in 9 of the studies, but "high" level IPM use by over 50 percent of the growers was only reported in 2 studies (Table 1).

In Texas, 82 percent of the cotton growers studied (Rajotte et al., 1987) were identified as IPM users. The Texas IPM program in cotton has a long history dating back to the original Extension IPM Pilot Project for cotton and tobacco which was initiated in 1971 (Good, 1973). In the pilot project, state extension services hired and trained scouts who provided IPM services to growers subscribing to the programs. Today, private pest control advisors who are part of the Texas Pest Management Association provide IPM monitoring services to a majority of Texas cotton growers. California also participated in this pilot project, and by 1973, over 200,000 acres of cotton (about 22% of the state total) were serviced by private pest management consultants (Norgaard, 1975). This number has increased to an estimated 80% of the California cotton acreage at present. The primary role of 'scouts' hired as part of the early Extension IPM programs was initially to monitor pest abundance or incidence, and then to recommend pesticide use based on reaching

control action thresholds. As these pest management consultants became private, their services often expanded to include consulting on all aspects of pest, nutrient and water management including the use of biological controls when appropriate. It is interesting to note that the case history reporting the greatest percentage of "high" level IPM users in the 1987 study was tobacco in North Carolina (Table 1), another target of the original Extension IPM Pilot Project (Carlson and Cooper, 1975).

Consultant focus. The development of a pest management consulting industry can be viewed as one of the positive effects of IPM implementation, and private consultants have become a major force in the delivery of pest management information to growers (Blair, 1986; Frisbie and McWhorter, 1986). The total number of pest control advisors in the United States is not known, but in California where individuals making pesticide use recommendations must receive state certification, over 3900 people are licensed. Use of IPM practices by pest control advisors is a good indicator of overall adoption or potential adoption because of their key role in grower's pest control decisions. However, the number of pest control advisors alone does not guarantee that IPM will be encouraged or adopted, only that IPM exposure is increased.

California pest control advisors are the target audience for research and extension efforts of the University of California's Statewide IPM Project which was funded by the state legislature in

1979. A 1987 survey of California pest control advisors conducted by Flint and Klonsky (1989) showed levels of use of 20 selected IPM monitoring techniques by the advisors ranged from 10.7 to 93.6 percent. The most widely adopted of the IPM techniques were those that have been available longest (e.g. monitoring cotton squares for *Lygus* damage, 81.5 percent; codling moth traps and phenology models in pome fruit, 93.6 percent), or those which have been actively demonstrated by the IPM Projects' extension staff (e.g. presence-absence spider mite sampling in cotton, almond, and citrus, 84.6, 70.6, 52.4 percent, respectively; peach twig borer traps and phenology models in stone fruit, 66.1 percent). Over 86 percent of the active pest control advisors have at least one of the University of California IPM manuals which are written for specific crops, and the average advisor had 3 or 4 manuals.

EMPIRICAL EVALUATION OF IPM

The literature on IPM contains numerous references which emphasize its advantage over conventional control in terms of increased production, greater net return, improved risk management, and lessened environmental impact both in general terms and on specific crops. Table 3 provides a list of selected studies which evaluate the crop specific impact of IPM on these factors. IPM development from the 1950's to mid 1960's was motivated more by

concerns over pesticide resistance, destruction of natural enemies, and economic reasons than concern about the environment. In the mid 1960's, with the emergence of DDT as an issue, environment became a factor. Even today, many growers and pest control scientists are driven by the specter of pesticide failure and economic issues as opposed to environmental concerns. While the general public has environmental quality as a prime concern, many individuals in government and research have not yet adopted an environmental agenda. Only recently, because of its significance to growers, has the economic advantages of IPM become more widely studied (c.f. De Wilde and Leemans, 1980; Reichelderfer, et al. 1984; Tait, 1982). In nearly every economic evaluation of IPM programs, it has shown increased profits at the farm and commodity level. This might be expected as analysis of the cost of pest damage and benefits of control using appropriate methods has long been central to IPM research methodology. Because conventional chemical pest control strategies have social and environmental impacts as well, economic benefits of IPM are even more pronounced.

Economic evaluation. IPM economic impact has been studied at different levels using different approaches. Significant differences exist in the approaches taken by biologists and economists. Bibliographies such as those by McCarl (1981) and Osteen et al. (1981) provide a relatively complete review of studies related to the economics of pest control and IPM. It is interesting to note, however,

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that most studies cited in these bibliographies were directed at estimating the benefits of pesticides, especially those which were the subject of Environmental Protection Agency review, rather than the benefits of nonchemical alternatives used in IPM systems.

The concept of economic injury level, or the estimate of pest density that can be tolerated without crop loss exceeding the cost of control, has been a central element of IPM since it was first proposed by biological founders of IPM such as Stern et al. (1959). Headley (1972), an economist, has defined the economic injury level as the pest population that produces incremental damage equal to the cost of preventing the damage. Another important parameter to biologists is the economic threshold which is defined as the pest population density at which control measures must be applied to prevent an increasing pest population from reaching the economic injury level (Stern et al., 1959).

Determining the economic injury level and economic threshold requires knowledge of pest biology and crop physiology as they relate to meteorology, naturally occurring biological controls, and the effects of possible control actions. They may vary from region to region, crop cultivar to crop cultivar, and even between fields depending on specific agricultural practices (Reynolds, 1972). The economic injury level is inversely related to product price and directly related to the cost of control (Headley, 1972). It is also a function of consumer quality standards. Changes in consumer

preference for crops, and governmental laws or industry standards regulating product quality can produce drastic changes in the economic injury levels for a given crop.

The application of standard economic costs and returns analysis has been the typical measure of IPM economic evaluation in most crop case studies, as data gathered by biologists to establish economic thresholds is what is most often available for determining economic benefits of IPM by economists. In rare instances (c.f. Carlson, 1970), the determination of economic injury is based upon consideration of long term management strategy that involves the dynamics of several pest generations or even several cropping seasons. Only under such scrutiny can the true long term biological and economic benefits of IPM be determined.

Pest control decisions, either those involving IPM or conventional chemical control technology, have environmental and social economic impacts. Benefits can arise from an increase in output over what would normally occur and from a saving of the resources needed to produce a constant output (Headley, 1975). If all costs and benefits of the technology applied are not considered by those making pest management decisions, society does not receive the maximum output from its resources. The issue raised in environmental arguments is that the costs of conventional chemical control does not fully state environmental and social costs, and

therefore the net benefits received from chemical controls is overestimated.

Case studies. As mentioned earlier, virtually all economic evaluations of IPM Programs show either the same or lower costs and greater net economic returns compared to conventional strategies (see Table 3 for examples). This is most often because of lower pesticide costs.

Some of the best examples in the literature are from cotton, where much IPM research and extension effort has been put forth nationally. This is especially true of several studies of the Texas cotton program. Lacewell and Taylor (1980) showed that implementation of the Texas High Plains boll weevil control program has provided an annual regional increase in economic activity of \$63 million, while benefitting the regions cotton growers by \$27 million. Implementation of a short season cotton program in the lower Rio Grande Valley showed increased annual profits for the areas growers of over \$11 million (Shaunak et al., 1982), primarily due to reduced insecticide costs and increased yield.

Regional management is often required to insure success of particular controls, particularly when host free periods are required to interrupt an insects life cycle. Such a regional IPM approach to controlling boll weevil in the Texas Rolling Plains, delayed uniform planting, was studied by Masud et al. (1985). Additional returns were estimated to be \$21.36 per acre for farmers using this cultural

control technique as opposed to former chemical control techniques. The average annual impact in the region for the period 1970 to 1982 was estimated at \$192 million. Risk, as estimated by the coefficient of variation for production during the period, was shown to be lower compared to conventional cotton production practices in the study. State enforced regional management of planting and plowdown dates for cotton, which was initiated by grower referendum in the San Joaquin Valley of California, is widely credited by University of California researchers (University of California, 1984) for preventing pink bollworms from becoming established despite annual invasions from the neighboring desert cotton producing valleys of Arizona and southern California. Insecticide use on the over 1 million acres of San Joaquin Valley cotton is among the lowest in the world, and in some years only 2 or 3 sprays are applied. This compares to over 7 sprays per year in the area prior to the first extension IPM pilot project in 1971 which featured demonstration of field scouting for cotton pests, and to an average of 15 to 18 sprays in the Imperial Valley of southern California where the pink bollworm became established in the mid-1960's.

Nationally, insecticide use on cotton has decreased since pilot extension IPM implementation projects were initiated in 1971. In 1971, an average of 5.8 pounds per acre were applied to cotton. This decreased to 5.5 pounds per acre in 1976, and 1.5 pounds per acre in 1982 (Frisbie and Adkisson, 1985). Of total pounds of insecticides

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applied to major field crops in 1976, cotton accounted for 49 percent. By 1982, cotton accounted for only 24 percent. Not all of this reduction can be attributed to IPM, however, as new pesticides such as the pyrethroids which utilize lower application rates were introduced during this time.

A similar dramatic decline in pesticide use has been observed in peanuts, another crop targeted in the pilot extension IPM implementation project (von Rumker et al., 1975), and which has subsequently received considerable research and extension attention throughout the southern United States. In 1971, 87 percent of peanut acreage was treated with an average of 3.9 pounds of insecticides per acre. By 1982, only 48 percent of peanut acreage was treated, and the average pounds per acre was less than 0.8 (Frisbie and Adkisson, 1985).

Not only annual crops benefit from the successful implementation of IPM research and extension programs. California almonds are a good example of a perennial crop where a complex of IPM techniques are being widely utilized by growers. Most of the techniques were developed over the decade of the 1970's, but were not widely promoted until 1979, when University of California extension staff and later the University of California's Statewide IPM Project targeted almonds for special attention. An evaluation of the almond IPM program was conducted by Zalom et al. (1987), who found that the relatively high level of adoption of portions of the

program could be measured on an industrywide basis in terms of increased crop quality and decreased pesticide use in the period after a benchmark study of the industry was conducted in 1980 (Headley, 1984). Reduced crop damage resulted in per annum revenues of \$4.94 million in increased production and \$3.33 million in quality adjustments. Pesticide use was reduced by 31.2% during the period for an annual saving of at least \$3.56 million. The percentage of almond acres treated decreased to only 53 percent.

As demonstrated by these case studies and many others, there is strong empirical evidence that when it is adopted, IPM results in economic benefit to growers and society, typically accompanied by reduction in pesticide use. In spite of this, IPM techniques are far from being universally adopted, even in many cases where convincing empirical evidence exists that IPM would be beneficial.

SOURCES OF IPM INFORMATION AND THE ADOPTION PROCESS

Education of the user is a key element in successful implementation of most technologies (Lasserre, 1982). This is especially true of complex concepts such as IPM (Lincoln and Blair, 1977; Poe, 1981; Smith, 1978). Recent studies such as that of Wearing (1988), who studied IPM delivery methods in the United States, Europe, and Australia, by interviewing IPM research and extension specialists, have generally shown that verbal

communication is the most effective method. Among verbal communication methods, one-on-one contact with consultants (including both private consultants and farm supply dealers) and with extension agents were rated highest (approximately 90 percent favorable), with meetings and demonstrations also rated highly (76 and 73 percent favorable, respectively). Wearing's study rated written communication sources as moderately to highly effective, with newsletters (83 percent favorable), articles (58 percent), and bulletins (56 percent) considered most valuable. Electronic sources such as film or video, computers, television, and radio were all rated lowest in utility with 82 to 89 percent seldom or never using the methods.

Grower education. Surveys have also been conducted on several crops during the past five years to determine IPM and general pest management information sources of growers. In these studies, it is often informative to distinguish between the types and complexity of information which is discussed. Pest management information might include simple pesticide use recommendations in addition to IPM concepts, while IPM information typically includes a variety of control techniques and management strategies.

Table 4 shows the degree of use of various sources of general pest management information. Although there is some variability between studies, some generalizations can be drawn. Extension agents or products of extension services and farm supply dealers are

often the leading sources of general pest management information, usually being utilized by over 50% of growers surveyed. Other growers and trade publications such as magazines and newspapers are also widely used sources of pest management information, but their utility was relatively more variable between the studies. Grower group and other agricultural industry associations were usually used less frequently than the other sources mentioned.

When growers who considered themselves high users of IPM were asked to identify their first source of contact with specific IPM techniques, extension agents and other extension sources were most often identified (Table 5). Trade publications on average were the next most identified sources of first contact with specific IPM techniques. Farm supply dealers were never as highly rated as extension agents or other extension sources for first contact with IPM techniques.

Studies such as these show the potential of extension agents, farm supply dealers, and one might assume private pest management consultants as change agents (Grieshop et al., 1988) who could accelerate the stages (awareness, interest, evaluation, trial, and adoption) through which potential IPM adopters pass in the decision making process.

Private pest management consultants. Extension services have traditionally provided a service to growers in the area of pest control advice. Following World War II, when synthetic pesticides became

widely used for pest control, farm supply dealers who marketed the pesticides also became important sources of information, often because they could provide more personalized service to growers than the extension service. These individuals also had good knowledge of this relatively complex new technology. The importance of the farm supply dealer in providing pest management information is still seen today (Table 4).

Pioneering IPM researchers such as Michelbacher and Bacon (1952), who first used the term 'integrated control' to describe methodologies for the selection, timing, and dosage of insecticide applications for the control of walnut aphid and the preservation of its natural biological control agents, provided the framework for growers to synthesize information about crop production, pest population levels and control techniques. Increasing environmental awareness and management problems (such as pest resistance to pesticides and outbreaks of pests previously under good natural biological control) which were associated with calendar based pesticide applications provided incentives for growers to seriously consider the use of alternative pest management strategies. Calendar based spraying was the prevalent pest control strategy of the 1950's and 1960's. Such sprays were applied on a regular schedule to prevent pest outbreaks, and were often considered to be a standard agronomic practice much like applying fertilizer or irrigation. Understanding IPM concepts and applying IPM techniques required

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additional labor in the form of monitoring pest abundance, and specialized knowledge of pest biology. Consultants who could provide the specialized service of monitoring the health of a grower's crops on a more frequent basis than extension agents were needed.

As early as the 1950's, a few pioneers began selling knowledge and information to their grower clientele, initiating what we now know as private pest control advising (or consulting) companies. Cox (1971), a private consultant himself, described the role and requirements of a private pest management consultant in the first detailed treatise on the subject. Increased IPM research activities in the 1970's accelerated the development of the private pest management consultant industry (Post, 1988). Requirements for continual monitoring of insects and diseases greatly increased the need and opportunity for the consultant. Some extension services began to train field scouts to monitor growers' fields on a fee basis, and later encouraged the services to continue in the private sector. Many of the scouts trained as part of the USDA extension IPM projects of the 1970's became private consultants themselves.

Private consultants have now become a major force in the delivery of information to growers in the Midwest (Blair, 1986). A survey of extension personnel by Post (1988) revealed that over 70 percent felt that private pest management consultants benefitted agriculture, and were experienced, educated and capable. Frisbie and McWhorter (1986) attributed the expansion of the private pest

management consulting industry in Texas to the expansion of extension IPM programs that demonstrated the need for pest management advice to growers. In contrast, the large number of consultants in California, perhaps the most of any state, is attributed to the state's regulatory and enforcement system Kendrick and Stimmann (1984). In the early 1970's, a program for licensing pest control advisors was initiated. The law requires anyone who recommends pesticides or any other pest control method or device for agricultural use, to be licensed. Growers and public sector employees are exempted. Some individuals (Willey, 1978; Wearing, 1988) suggest that the registration of pest control advisors in California has not had a material effect on IPM in practice because the licensing program does not distinguish private consultants from the majority who work for farm supply dealers or other chemical retailers.

Post (1988) listed five reasons why growers employ a private pest management consultant:

1. The rapid discovery of new technology and the grower's inability to keep abreast of these findings.
2. Increasing government controls and the need for help in complying with pesticide and other regulations.

3. Low profit margins and the necessity to farm efficiently without loss from unexpected insects or diseases.
4. The need for a "direct line" through the consultant to researchers for accurate and timely agricultural information.
5. Continual access to an advisor that is totally loyal.

He also believes that because farm management is becoming more precise and demanding, the grower does not have adequate time for both business and crop production. Another reason for growers to employ a private pest management consultant is to transfer liability.

Lambur et al. (1989) surveyed 136 private pest management consultants from 45 states to determine their sources of pest management information. Extension bulletins, manuals and handbooks (81.3 percent); the consultants own research (79.7 percent); extension specialists (usually Land Grant campus-based) (79.3 percent); extension newsletters (72.2 percent); and the consultant's own scouts (70.0 percent) were reported as the top five information sources. Only 44 percent of the consultants considered county-based extension agents as useful sources of pest management information. Extension electronic information methods such as radio (11.8 percent), computer networks (11.4 percent), telephone recordings (9.7 percent), videotape (3.0 percent), videotext (2.3

percent) and television (2.2 percent) were considered useful by the fewest private consultants surveyed.

CONSTRAINTS TO IPM ADOPTION

In order to assess potential incentives for grower and consultant utilization of IPM, it is useful to examine possible constraints to adoption (c.f. Dover, 1985; Sorensen, 1988). As mentioned earlier, IPM has received much attention as the only rational approach to providing long-term solutions to pest problems. It has been demonstrated in studies such as those mentioned earlier to provide benefits such as reduced risk of pest damage, increased net profits, and reduced pesticide use. Despite the preponderance of such results, IPM systems and practices, even when available and demonstrated to be effective, are far from being universally adopted by growers and farmers throughout the United States in spite of rising pesticide costs (Samuel, et al., 1983) and increasing resistance to pesticides (National Academy of Sciences, 1986).

A large number of constraints to IPM use have been identified in various studies (c.f. Corbet, 1981; Grieshop, et al., 1988). Wearing (1988) categorized these obstacles as technical, financial, educational, organizational (institutional), and social. In his study of IPM in the United States, Europe and Australia/New Zealand, all of these general obstacles were identified as important, but their relative rank varied.

Technical constraints. Technical obstacles, primarily the development of IPM strategies and techniques such as monitoring guidelines, control action thresholds, biological controls, cultural controls, and host plant resistance, are often regarded to be less important than other general obstacles to IPM adoption (c.f. Gruys, 1982; Perkins, 1982). The need to simplify IPM methodology is especially important, particularly with respect to developing monitoring and sampling guidelines, and control action thresholds (Arends and Robertson, 1986; Corbet and Smith, 1976; Goodell, 1984; Hussey, 1980). Wearing (1988) found that private pest management consultants (50 percent) and extension agents and specialists (52 percent) perceived these to be more important technical constraints than researchers (27 percent), probably reflecting their relationship to practical application. Similarly, Flint and Klonsky's (1989) study of California pest control advisors rated research on monitoring and thresholds to be their highest rated technical need, followed in order by cultural control methods, biological control methods, economic analysis of controls, pesticide resistance studies, crop and pest interaction studies, and computer simulation models. Lack of selective pesticides and selecting IPM compatible pesticides are also mentioned as major technical obstacles in some studies (c.f. Croft, 1978; Gruys, 1982; Newsom, 1975).

Financial constraints. IPM often increases net profits for adopters. However, there is still a perception by growers that IPM

does not offer short-term economic advantages compared to conventional control, particularly because of additional labor costs from sampling and monitoring (Poe, 1981). Private pest management consultants and others who provide IPM services must charge for providing what many growers consider to be pest control advice, a service which has traditionally been provided at no outward charge by representatives of farm supply dealers who also sell farm chemicals. Growers expect to budget for tangible items such as machinery, pesticides, and fertilizers, but the concept of purchasing advice is still less acceptable. Further, paying for advice in advance of pest problems or if no pest problem occurs is difficult for growers to accept. Growers must be convinced that IPM advice has value. Private pest management consultants are constrained from adopting more time-consuming IPM technologies in order to provide their services at the lowest possible cost.

Most consultants receive \$3.00 to \$8.00 per acre per season for field crops and \$12.00 to \$25.00 per acre per season for perennial crops depending on location, crop value, and competition. While some consultants have developed successful businesses, long hours, lack of liability insurance, and low to moderate pay in relation to level of education has kept many qualified individuals from entering the field (Whalon and Weddle, 1986). Cooperative IPM programs, in which farmers share costs and losses have been tried successfully for

citrus in California (Graebner, et al., 1984) and for cotton in Texas (Frisbie, et al., 1983).

Risk is probably the most important financial obstacle to IPM adoption. Growers value pesticides for reducing production risk as well as contributing to profit. It is very important that IPM can be shown to decrease this risk (Way, 1977; Gruys, 1982; Antle and Park, 1986). In reality, IPM strategies such as monitoring are tools for managing risk. The more growers learn about pests in their fields and the likelihood of resulting damage, the less is the uncertainty in their minds about the state of their crop and the more likely it becomes that they will not choose to make a preventative pesticide application. Antle (1988) believes that the value of IPM in terms of risk reduction should actually increase in relation to the grower's level of risk aversion.

Lack of funds for extension programs has been cited as a constraint to IPM adoption in many studies (c.f. Frisbie and Adkisson, 1985; Tauber, et al., 1985; Whalon and Croft, 1984). Indeed, where such projects as the federal extension pilot projects of the 1970's and the state-supported IPM projects (including those of California, New York, and Texas) have been initiated, enhanced IPM adoption can be documented as described in an earlier section of this paper. At present, most extension IPM activity occurs at the state level with a combination of state support and Federal formula funds. The Federal funds have not increased during this decade, and the states where

major extension IPM efforts are occurring (California, New York, and Texas, for example) are those which have significant state contributions. Lack of funds for commercial development of biological control agents (Hussey, 1985) and biological pesticides including bacteria, fungi, and viruses, has limited their availability and increased their price.

Other financial obstacles include a commodity's value which can affect the production and marketing objectives of a grower, and loan and contractual commitments of growers which require growers to follow what is considered prudent practices to meet yield or quality objectives (van den Bosch, 1978).

Educational constraints. IPM is a complex set of behaviors, decision-making procedures, methods, technologies, and values organized to provide efficient alternative methods of pest management (Apple and Smith, 1976). Implementation of any such complex innovation requires intensive education of users. In the case of IPM this includes growers, pest management consultants, and extension staff. Methods of educating IPM users was described earlier, and likely could be improved with more innovative and targeted programs.

It has been suggested that lack of education of IPM developers about the perceptions and needs of growers could be a greater obstacle to adoption than the reverse (c.f. Goodell, 1984; Reichelderfer, et al., 1984). Such lack of understanding can lead to

development of inappropriate technology which will never be adopted.

Institutional constraints. The structure and edicts of regulatory, educational, and corporate or industry institutions can influence the implementation and expansion of IPM programs. Lack of coordination can be especially problematic (Kuhr, 1981; Perkins, 1982), especially among organizations, personnel, and disciplines. Both IPM research and implementation can be affected.

Recent pesticide legislation including the Endangered Species Act of 1973 (Federal), the Birth Defects Prevention Act of 1984 (California), the Safe Drinking Water and Toxic Enforcement Act of 1986 (California, Proposition 65), and the Pesticide Contamination Prevention Act of 1987 (California) has received much publicity in the popular press. It has been suggested that these laws may actually hinder the use of some IPM programs that rely on specific pesticides or application techniques that may be less disruptive to production systems than conventional pesticides that may not be affected by legislation. The survey of California pest control advisors by Flint and Klonsky (1989) revealed that 55.5 percent felt the impact of such legislation on IPM programs would be significant, 37.6 percent indicated it would be slight, and 6.9 percent indicated it would have no effect. Of the advisors who felt the impact would be significant, most thought that the use of IPM would actually increase because of increased legal requirements and grower awareness of

pesticide hazards. Only 21.1 percent thought that some IPM programs would be discontinued because of loss of materials required for specific programs.

Efforts to mandate or regulate IPM specifically have not heretofore been highly successful. Grieshop, et al. (manuscript in press) studied a mandated IPM program for lessees on state-owned land in California in which adoption quickly declined when no enforcement action was taken for noncompliance. It was found that the principle state agency involved, the Department of Parks and Recreation, lacked experience in dealing with agricultural production within a state park, and failed to adequately address grower concern for risk. Growers lacked confidence in research and extension efforts conducted at the request of the regulatory agency. Their efforts were perceived to be too closely linked with regulation. California regulations mandating the licensing of anyone making pest control recommendations were intended in part to foster the use of IPM strategies and tactics. However, because distinctions were not made between private pest management consultants and the majority of licensees who work for farm supply companies, these regulations may not have had the desired effect (Willey, 1978).

Some government programs can indirectly affect IPM adoption. Examples include commodity price supports which reward growers for maximizing production often at the expense of increased pesticide use which would not be profitable in the absence of support, and

marketing orders which may use low pest damage standards as tools which regulate supply. Farm subsidy programs encourage growers to plant the same crop each year to qualify for benefits. This discourages crop rotation, an effective cultural control for many species of insects, diseases, nematodes and weeds.

The lack of interdisciplinary collaboration in IPM research, extension, and teaching has been a major constraint voiced by many individuals (c.f. Barnett, 1981; Brader, 1980; Miller, 1983). There is a tendency for research and educational activities at the Land Grant Universities to be conducted within strong disciplinary-oriented departmental units (e.g. agronomy, plant pathology, entomology, etc.) which have evolved in response to institutional pressures for specialization. Individual achievements rather than team accomplishments are typically rewarded (Pimentel, 1982), leading to the predominance of such efforts at the expense of true cropping system studies involving biological, social and economic components. Degree programs which would lead to interdisciplinary professional rather than research degrees in plant health and pest management are few, and not well supported within our universities (Kendrick, 1988).

Other organizational obstacles also exist, most notably cosmetic standards imposed by government agencies such as the Federal Food and Drug Administration, the United States Department of Agriculture, and state departments of agriculture; corporations .

including processors, packers, and retailers; and commodity associations such as cooperatives and marketing orders (Corbet, 1981; Fenemore and Norton, 1985). These quality standards have largely been imposed in response to consumer concerns, but have also been used as market regulating tools.

Social constraints. Wearing (1988) found that social and marketing obstacles rated above all others for their impact on IPM implementation. Diffusion theory (Rogers, 1971) states that any new technology diffuses through a social system in a predictable manner. Initially, only a few members of the social system will adopt a technology. The number of individuals adopting the technology increases through time until the social system is saturated.

In agriculture, the rate at which the adoption process occurs and the ultimate level of adoption may be affected by many factors including demographic attributes of the agricultural population, communication channels used by growers or managers, and growers' perceptions of the technology.

In two studies, grower age tended to be a factor in IPM adoption with growers under 50 years of age tending to adopt (Rajotte, et al., 1987; Zalom, et al., 1987), although statistically significant differences were not shown in either study. Grower education level appears to be only a minor obstacle to IPM adoption (Wearing, 1988), but higher levels of adoption tend to occur when the grower has at least some college education (Rajotte, et al., 1987).

At least one study (Grieshop, et al., 1988) has shown that land owners adopt IPM more readily than nonowners, and that the legal description of the farming operation was also significant.

Corporations, corporate partnerships and family farms all adopt IPM more readily than partnerships or family partnerships, possibly due to greater perceived risk to partners through such business arrangements. Farm size has not been shown to be a statistically significant factor for IPM adoption in any study.

As described earlier, growers receive pest management information from a variety of sources. In this regard, chemical controls have a competitive advantage over IPM. There is a well established infrastructure for pesticide supply and use, with a high ratio of chemical sales personnel, technical representatives, and farm supply dealers to private pest management consultants or extension IPM staff (van den Bosch, 1978; Smith and Pimentel, 1978). Further, corporations expend large amounts of resources in marketing agricultural chemicals, and use market analysis effectively to identify and improve market fit (Tait, 1982). Wearing (1988) cited lack of marketing expertise by IPM extension staff and consultants to be a major obstacle to implementation.

Agricultural chemicals are still perceived to be easy to use in spite of regulations on their use and application. Costs associated with application have increased, however, because of additional equipment, maintenance, and reporting requirements. Perhaps more

growers are using custom applicators as an alternative to purchasing and handling pesticides themselves. In addition, pesticides give growers immediate reinforcement in terms of pest control. Therefore, most growers have developed confidence in their use (Corbet, 1981; Hussey, 1985; Way, 1977). IPM on the other hand often requires more labor or specific knowledge, and takes longer to realize benefits. In addition, the concept of economic thresholds, which implies tolerating a number of pests in the crop, is perceived as risky by many growers (Pimentel, 1982). Experience with IPM can change this perception. Grieshop, et al. (1988) found that growers they studied who used IPM had significantly more confidence and satisfaction in IPM than did growers who did not use IPM. IPM users also perceived IPM as less risky, less time consuming, and easier to use than did nonusers.

INCENTIVES FOR IPM ADOPTION

Growers adopt IPM for many reasons, but by far the most important factor in all studies (c.f. Blair and Parochetti, 1982; Grieshop, et al., 1988; Newsom, 1980; Whalon and Croft, 1984) is the potential for financial gain either from reduced pesticide use, increased production, or reduced pest damage. As illustrated by Wearing (1988), long-term benefits are rarely cited as significant factors in adoption, as opposed to short-term benefits. Recently, in

response to public concern for food safety, some large grocery chains have begun to market produce as containing "no detectable residues", with IPM being used as one marketing tool in advertisements (Anonymous, 1988). The potential for entering new or premium marketing channels is causing some growers to reconsider their pesticide use practices. In New York, a certification program for growers who produce their crops using IPM practices is being initiated by the state regulatory agency at the request of growers following guidelines being developed by the IPM Program of Cornell University (J. Tette, personal communication, April 25, 1989). It seems likely that financial incentives or disincentives provided through government programs would have an impact on adoption of IPM and other low-input agricultural methods.

A crisis in pest control (Norton, 1982) such as resistance to pesticides (c.f. Corbet and Smith, 1976; Graebner, et al., 1984; Hussey, 1985), loss of key pest control materials due to regulation (Zalom, et al., submitted), or severe secondary pest outbreaks is another important incentive to IPM adoption. Because the rate at which agricultural chemicals are being registered has significantly declined, fewer conventional chemical alternatives are available and more frequent occurrences of this phenomenon might logically be expected.

Environmental and on-farm health and safety concerns were an important stimulus to IPM research, but they have typically

contributed to adoption only because of some obvious problem or because of regulation resulting from a concern or problem (Tarlock, 1980). Among environmental issues, grower concern for conservation of specific natural enemies is most important (Wearing, 1988). Growers rated protection of personal and public health and reduced environmental damage as the 2 least important incentives for adopting IPM in the national evaluation of extension IPM programs (Rajotte, et al., 1987).

POTENTIAL POLICY OPTIONS

Any approach that reduces the use of pesticides will lower the probability of their introduction into groundwater. IPM is one approach which can incorporate expert opinion on the potential for pest damage with the use of such environmentally safe tactics as biological controls, behavioral chemicals, cultural controls, and host plant resistance. Addressing the constraints to IPM adoption would seem logical. Policy to enhance IPM could be directed at the entire United States agricultural system from research and extension through production and marketing.

Agricultural research and extension. Although many research and extension professionals are involved in IPM activities in Land Grant Colleges, the USDA, and private companies, the level of activity is insufficient to meet the demands that would be necessary to

develop and implement IPM programs universally in the United States. The obvious response would be to direct more funding to the present system. While this would undoubtedly be beneficial, perhaps a more careful examination of institutional structure and incentives to researchers is needed as well. Most aspects of IPM research require an extensive understanding of the crop ecosystem, and strong interdisciplinary programs. While some of this research is considered quite technical, especially to those growers or consultants trying to apply the research, development of biological controls, cultural controls, and decision rules in IPM are not considered highly technical by university colleagues reviewing promotion or tenure packages or by granting programs such as USDA Competitive Grants, National Science Foundation, etc. in the same way as is research in more fundamental areas of science such as genetics or biochemistry, for example. Therefore, researchers are directed away from field studies because of a lack of institutional support. Applied ecology, which was emphasized in the 1960's and in agriculture has led to many of the alternatives that are now possible to use, has been replaced in emphasis by molecular biology and genetic engineering. Many positions in Land Grant Colleges which were once filled by individuals conducting field studies are now directed more toward individuals who have a strong laboratory bias. Even for those researchers who have an interest in pursuing studies of applied ecology, there is little incentive to do the adaptive

research necessary which could lead to commercial implementation. Adaptive research, often a critically important part of the implementation process, typically occurs today by individuals in Cooperative Extension or the private sector. Unfortunately, unless these individuals were part of the original research or unless the original researcher is willing to continue to be active in the adaptation of their research, the probability for failure in these efforts is great. In addition, many adaptive studies result in useful applications, but not in products which could be protected by patent or copyright laws and are therefore not of interest to the private sector.

Greater investment in research and extension, while necessary, should be accompanied by mechanisms which would address both near term and long term problems associated with conversion to an agricultural production system based on lower pesticide use. Research and extension funding programs should be more goal-oriented, no matter what the time frame of the proposals. Individuals designing and administering these programs should clearly identify the goals of the programs, and research and extension should be closely linked in both the development and implementation of the programs. Research and extension specialists should be required to address how the results of their efforts will contribute to the goals of the program, and this requirement should be given equal consideration to scientific merit in funding decisions.

It is disconcerting when individuals doing agricultural research at Land Grant Institutions have no concept of the potential utility of their work, and when there is no institutional mechanism in place for insuring accountability. This phenomenon is not uncommon, and is actually well-entrenched because of the peer-review process in decisions affecting grants, promotion, and tenure.

It may be possible to redirect public sector research efforts by concentrating more funding in the area of transitional research, the interface of more basic studies and the field level of IPM use. An emphasis on goals as described previously would be essential to achieve successful results. Research programs in the USDA or the Agricultural Experiment Stations should specifically address this area and must receive adequate support. Consideration should be given to affording 11 month (in effect full time) appointments only to Agricultural Experiment Station researchers who are willing to focus their research on such goal-oriented research, and 9 month appointments to others. Position descriptions clearly stating the goals of an individuals research should be required of scientists with such appointments, and adherence to position goals considered for promotion. The same argument could be made to enhance research efforts in biological and cultural pest controls.

More positions in Cooperative Extension should be directed specifically at the area of IPM implementation including biological and cultural pest controls, and this should be accompanied by a

sufficient level of funding. In most states, there are far more staff with expertise in production than pest management. The agricultural chemical industry has an established infrastructure in marketing products to growers which gives it an advantage over public and private promoters of IPM. For example, in Fresno County, California (W. Barnett, personal communication, April 27, 1989), 5500 farms are serviced by over 500 licensed pest control advisors, a majority of whom work for pesticide retailers. Only 3 Cooperative Extension staff have pest management responsibilities in that county with only 1 directed specifically to IPM.

Private sector incentives for developing and marketing biological controls and biological pesticides should be made to interest more companies in their development and production, and to hasten their use. This might take the form of grants or tax incentives. Some allowances for biological pesticides, including fungi, viruses and bacteria, and other alternative pesticides such as pheromones, have been made which exempt certain aspects of registration. Legislation making it less expensive for companies to register these materials by further exempting some requirements would be beneficial. This is especially important because the selectivity of these materials and the rapidity of the degradation, both environmentally beneficial attributes, also limit their potential market when compared to more traditional pesticides.

Private pest management consultants. Implementing IPM is best achieved by individuals well trained in pest management and the plant sciences. The success of private pest management consultants in reducing pesticide use through implementing IPM strategies and techniques is well documented. However, the number of private pest management consultants is limited. Increasing the utilization of private pest management consultants could be accomplished by increasing grower incentives, or by licensing these individuals and requiring their direct input in the pesticide use process. Degree programs which would lead to professional accreditation in plant health and pest management should be supported at Land Grant colleges in much the same way as are veterinary schools, and they could be structured as graduate groups or professional schools at those institutions.. No comprehensive programs currently exist at any Land Grant institutions, but some attempts have been made at both the undergraduate and masters degree levels. Plant health practitioners who would graduate from such programs, like their veterinary or medical counterparts, would be permitted to prescribe the use of restricted agricultural chemicals in response to careful monitoring of the crops health and in accordance with label requirements.

An immediate need for private pest management consultants, and a deterrent to some potential practitioners is access to insurance. At present, only 1 company has indicated a willingness to provide

insurance for this relatively new profession (P. Weddle, personal communication, December 18, 1989). Federal or state underwriting or guarantees for such insurance would allow individuals to become practitioners without the fear of excessive personal loss, and might encourage at least a few individuals to enter the profession.

Marketing. Regulations on allowable damage imposed by government agencies, marketing orders and private packers or processors are warranted when health standards are at issue. However, some registrations are granted which only contribute to cosmetic enhancement, and are justified on the basis of consumer demand for quality. In practice, restrictions on allowable damage can also be used to regulate markets by those industries affected by the restrictions. Careful distinctions should be made between acceptable damage levels that have health benefits and those that are strictly cosmetic.

Commodity price supports reward growers for maximizing production and encourage growers to plant the same crop each year to qualify for benefits. An emphasis on production often results in increased pesticide use which would not be economical at lower commodity prices. These programs also discourage crop rotation, an effective cultural method to interrupt the life cycles of insect, disease, nematode, and weed pests. Impact upon pesticide use should be a consideration in such support or incentive programs. Rewarding growers for producing crops with lower pesticide use

instead of simply maximizing production would be a significant policy statement.

Government certification might be an incentive for consumers to purchase products grown using IPM practices. Certification would require a set of crop-specific IPM standards which a grower would need to follow in order to meet requirements. This is similar to current activity in defining and certifying organically grown products. It would be difficult to regulate any such program as is currently the case for organic products, but it might be possible for growers groups to insure compliance through examination boards or through requiring use of private pest management consultants in making pesticide decisions.

Any policy which will increase the probability that smaller amounts of pesticides will be applied will tend to decrease the chances that pesticides will reach groundwater. Thus, policies which demand careful consideration of need for any particular application will reduce the environmental pesticide burden. Policies which disconnect those who recommend pesticides from income obtained from pesticide sales should be encouraged. The primary incentives driving pesticide use should be efficient, cost effective crop production, and worker and environmental protection.

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PERSONAL COMMUNICATION

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GLOSSARY

- beneficial organism - a species which provides a positive impact upon a given systems.
- biological control - the use of natural enemies (predators, parasites and pathogens) to reduce a pest population.
- control action threshold - levels of pest abundance at which some action must be taken to protect a crop from unacceptable economic loss.
- farm supply dealer - retailers who market various agricultural products including fertilizers and pesticides.
- genetic engineering - the transfer of genetic material governing specific functions or characteristics to another organism.
- integrated pest management - the systems approach to reduce pest damage to tolerable levels using biological controls, cultural controls, genetically resistant hosts and when appropriate chemical controls, especially those which are not selective and do not contribute to environmental contamination.
- natural control - the action of native species in limiting the abundance of a pest species.
- non-target organism - something, usually a non-pest species, affected by an action intended to control a pest species.
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pest control advisor - any individual who recommends pesticides or any other pest control method or device for agricultural use. These individuals must be licensed in California and some other states.

pesticide - any material applied to control a pest species.

pheromone - a chemical released by insects which affect the behavior of members of their own species.

private pest management consultant - (also private consultant or crop consultant) any individual who provides an information service to growers for a fee, advising on various aspects of crop production including pesticide use.

Table 1. Percentage of growers in the 1984 national evaluation of extension IPM programs identified at IPM users (data taken from Rajotte, et al., 1987).

State(s)	Crop	Level of IPM Use		
		Non	Low	High
CA	Almond	34.5	16.4	49.1
GA	Peanut	20.7	19.7	59.6
IN	Corn	31.0	27.2	41.8
KY	Stored grain	68.0	11.0	21.0
MA	Apple	48.9	¹ /	-
NY	Apple	19.3	73.4	7.3
TX	Cotton	18.0	² /	-
VA	Soybean	25.1	25.1	49.8
ID,OR,WA	Alfalfa seed	26.4	34.8	38.8

¹/51.1% of growers were identified as IPM users.

²/82.0% of growers were identified as IPM users.

Table 2. Adaption of specific IPM practices by California almond growers (Zalom et al., 1987).

Target Pest(s)	Intent	Recommended IPM Practice	1981 N=231	1985 N=215	Percent Change
Navel orangeworm	Control	Winter Sanitation (pole nuts from trees)	48.1	65.8	36.8
Navel orangeworm	Control	Winter Sanitation (shake nuts from trees)	20.8	31.2	50.0
Navel orangeworm	Control	Winter Sanitation (destroy nuts on ground)	55.4	75.6	36.5
Peach twig borer & San Jose scale	Control	Dormant sprays	79.7	92.8	16.4
Navel orangeworm	Control	Harvest before peak adult flight	53.2	80.3	50.9
Navel orangeworm	Control	Fall Sanitation (pickup nuts on ground)	84.0	97.7	16.3
Navel orangeworm	Control	Fall Sanitation (pole after shaking)	73.6	82.8	12.5
Ants	Control	Artificial drying of harvested nuts	11.3	33.6	97.3
Navel orangeworm	Control	On farm fumigation of harvested nuts	10.4	26.8	57.7
Navel orangeworm	Monitor	Egg traps	34.8	49.8	43.1
Peach twig borer	Monitor	Pheromone traps	25.8	39.5	53.1
San Jose scale	Monitor	Pheromone traps	N/A	16.3	N/A
Oriental fruit moth	Monitor	Pheromone traps	N/A	23.7	N/A
Spider mites	Monitor	Leaf sampling for mites	N/A	67.9	N/A

Table 3. Selected studies which evaluate impact of IPM on pesticide use, production and risk.

State & Source	Crop	Effect of IPM on			
		Pesticide Use or Cost	Yield	Net Return	Level of Risk
IL,WI McGuckin, 1983	Alfalfa	Decreased	-----	Increased	Decreased
CA Zalom et al., 1987	Almond	Decreased	Increased	Increased	-----
CA Batiste et al., 1973	Apple	Decreased	-----	-----	-----
MA White & Thompson, '82	Apple	Decreased	-----	-----	-----
MA Whalon & Croft, 1984	Apple	Decreased	-----	Increased	-----
MI Howitt et al., 1966	Apple	Decreased	-----	-----	-----
NY Thompson et al., 1980	Apple	Decreased	Constant	-----	-----
NY Prokopy et al., 1973	Apple	-----	-----	Increased	-----
WA Eves et al., 1975	Apple	Decreased	-----	-----	-----
WA King & O'Rourke, 1977	Apple	Decreased	-----	-----	-----
AK Teage & Schulstad, 1981	Cotton	Decreased	-----	-----	-----
CA Hall, 1977	Cotton	Decreased	No Impact	No Impact	Decreased
CA Huffaker, 1980	Cotton	Decreased	-----	-----	-----
NC Carlson, 1979	Cotton	-----	-----	-----	Decreased
TX Sprott et al., 1976	Cotton	Decreased	Increased	Increased	-----
TX Lacewell et al., 1977	Cotton	-----	-----	Increased	-----
TX Clarke et al. 1980	Cotton	-----	Increased	Increased	-----
TX Masud & Lacewell, 1985	Cotton	Decreased	Increased	Increased	-----
TX Masud et al., 1981	Cotton	Decreased	Increased	Increased	-----
TX Lacewell et al., 1974	Cotton	Decreased	Increased	Increased	-----
TX Lacewell et al., 1976	Cotton	Decreased	-----	-----	-----

Table 3. (continued)

State & Source	Crop	Effect of IPM on			
		Pesticide Use or Cost	Yield	Net Return	Risk Level
TX Casey et al., 1975	Cotton	Decreased	Decreased	-----	-----
TX Lindsey et al., 1976	Cotton	-----	-----	Increased	-----
OK Von Rumker et al., 1975	Peanut	Decreased	Increased	Increased	-----
CA Carlson, 1970	Peach	-----	-----	-----	Decreased
GA Reichelderfer, 1979	Pecan	Decreased	-----	Increased	-----
IL Moffitt et al., 1982	Soybean	-----	-----	-----	Decreased
VA Rajotte et al., 1987	Soybean	Decreased	-----	Increased	-----
VA Allen & Roberts, 1974	Soybean	Decreased	-----	Increased	-----
VA Greene et al., 1985	Soybean	Decreased	-----	-----	-----
NC VonRumker et al., 1975	Tobacco	Decreased	-----	Increased	-----
CA Antle & Park, 1986	Tomato	Decreased	Increased	Increased	Decreased
NC Weathers, 1979	Corn	Decreased	Increased	Increased	-----
	Soybean	Decreased	Increased	Increased	-----
	Peanut	Decreased	Decreased	Increased	-----
IN Lazarus & Swanson, '83	Corn	-----	-----	-----	Increased
	Soybean	-----	-----	-----	Increased
GA Hatcher et al., 1984	Cotton	-----	Increased	No Impact	-----
	Peanut	-----	Increased	Increased	-----
	Soybean	-----	Increased	Increased	-----

Table 4. Percentage of growers utilizing various pest management informational sources in selected studies (Zalom et al., 1987, Rajotte et al., 1987).

Informational Source	State and Crop									
	WA, OR Alfalfa Seed	CA Almond	MA Apple	NY Apple	IN Corn	TX Cotton	GA Peanut	VA Soybean	KY Stored Grain	NC Tobacco
Extension Agent	55.5	69.3	74.4	65.9	52.9	79.5	96.8	74.1	37.5	79.0
Farm Supply Dealer	66.3	66.8 ^{1/}	60.7	78.3	37.7	45.0	75.8	60.9	50.6	61.0
Extension Publications	67.9	65.9	83.3	88.0	64.0	59.0	91.5	82.9	51.9	85.8
Extension Meetings	74.1	45.8	2/	66.8	58.3	-	94.7	45.7	62.2	58.2
Other Growers	73.9	62.6	35.7	37.3	54.1	34.7	74.2	71.1	44.4	62.7
Trade Publications	46.9	45.2	29.4	40.7	59.9	25.4	81.9	63.3	31.3	49.7
Grower/Industry Groups	36.1	56.4	-	-	-	-	77.1	-	35.4	-
Electronic Sources	18.1	<10.0	-	74.2	23.6	40.2	61.4	25.5	33.3	35.0
Private Consultants	-	66.8 ^{1/}	-	23.5	26.7	77.2	25.7	10.2	-	14.4

^{1/}Private consultants and farm supply dealers are not differentiated in this study.

^{2/}Source not available as a survey choice.

Table 5. Percentage of high IPM use growers surveyed in relation to the source of their initial contact with IPM 1987, Grieshop et al., 1988).

Source of Initial Contact	State and Crop							
	WA, OR Alfalfa Seed	CA Almond	MA Apple	NY Apple	GA Peanut	VA Soybean	KY Stored Grain	CA Tomato
University Specialist	36.3	- ^{1/}	-	-	-	55.4 ^{2/}	10.5	17.8
Extension Agent	19.8	27.2	-	-	85.1	55.4 ^{2/}	63.2	24.8
Extension Newsletter	-	-	34.2	30.8	-	-	-	-
Meetings	-	-	31.7	15.4	-	-	-	5.7
Trade Publications	18.0	25.0	-	-	7.6	22.8	15.8	16.6
Private Consultant	6.1	7.4	-	-	-	-	-	22.3
Farm Supply Dealer	5.2	16.9	-	-	-	1.0	14.9	5.3
Other Grower	7.5	4.7	0.0	15.4	4.2	3.0	0.0	7.0
Other	7.5	18.8	34.1	38.4	2.1	3.9	5.2	5.8

^{1/}Source not available as a survey choice.

^{2/}Extension Specialists and agents were not distinguished in this study.

***IRRIGATION/CHEMIGATION: IMPLICATIONS
FOR AGRICHEMICAL CONTAMINATION OF GROUNDWATER***

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I. ABSTRACT

Groundwater aquifers contain about 86% of the total U.S. water resources and are a major source of both drinking and irrigation water. Thus, potential contamination of groundwater by agrichemicals is a major concern. Used on over fifty million acres of U.S. crops, irrigation is essential for crop production in arid areas, will increase crop yield or quality every year in semiarid areas, and insures consistent crop yield and quality in subhumid and humid areas. Application of excessive quantities of irrigation water or the nonuniform distribution of irrigation water can cause runoff or deep percolation of water and dissolved chemicals to groundwater. Most irrigation acreage expansion since 1945 has occurred with the installation of sprinkler irrigation systems in areas located over major groundwater aquifers. Both nitrate-nitrogen and pesticide contamination of groundwater have been measured in several regions with much of it likely due to agricultural practices. A significant potential for both nitrate and pesticide contamination exists in many major groundwater areas of the U.S. These areas of potential groundwater contamination appear to be concentrated in the humid, subhumid, and Central Great Plains regions, the same regions where sprinkler systems are the dominant mode of irrigation.

Several available and emerging irrigation scheduling technologies such as soil moisture measuring devices and automated microprocessor based scheduling systems can significantly improve scheduling of the timing and amount of irrigation water to be applied. Surge flow and cablegation systems can significantly reduce the potential for deep percolation and high volume tailwater from surface irrigation systems, thereby reducing the potential impact of these systems on groundwater contamination.

Chemigation is a relatively new agrichemical application technology which depends upon irrigation water for transporting and distributing agrichemicals. Improper chemigation backflow prevention systems can potentially allow agrichemicals to flow back into irrigation wells. Appropriate regulations and guidelines for chemigation backflow prevention systems have been developed. An estimated 34% of the 1989 U.S. irrigated acreage was chemigated at least one time. The overwhelming majority of chemigation is conducted with sprinkler irrigation systems. Since chemigation is utilized primarily with sprinkler irrigation systems which are located over major groundwater aquifers, advancements in chemigation technology offer significant potential for reducing the potential of groundwater contamination by agrichemicals.

Significant existing and emerging irrigation/chemigation technologies that could reduce the potential for groundwater contamination by agrichemicals are: (1) more widespread utilization of advanced irrigation scheduling techniques, (2) adoption of improved irrigation uniformity technologies, (3) design of irrigation systems to enhance chemigation, (4) development of agrichemical formulations particularly suited to chemigation, (5) development of performance standards and reliability testing procedures for chemigation backflow prevention systems, and (6) exploitation of the agrichemical application scheduling diversity offered by chemigation.

II. INTRODUCTION

Water is essential for all plant growth. Growing plants absorb water from the soil through their roots. As water in the plant root zone is depleted, the plant's ability to extract sufficient water decreases. Photosynthesis by the plant is correspondingly reduced, resulting in decreased crop yields and quality. Rainfall or irrigation must replenish the depleted soil water as the crop season progresses or crop growth and yield will be significantly reduced.

The availability of water for plants during their growing season is the most limiting factor in crop production. Crop yield and/or quality is always reduced when a shortage of soil water occurs. Severe shortages of rainfall or long periods between rains can drastically reduce crop yields in humid and subhumid areas as well as semiarid and arid areas. Crop production in arid areas is generally not possible without irrigation, while irrigation will increase crop yield or quality every year in semiarid areas. Even in humid areas, optimal soil water conditions for plant growth seldom occur (Cast, 1988). Thus irrigation is generally practiced where the benefits outweigh irrigation costs. Benefits of irrigation can be defined as: (1) increased or predictable yields, (2) improved product quality, and (3) reduced risks of production.

Chemigation is defined as the application of a chemical (fertilizer, herbicide, insecticide, fungicide, nematicide, etc.) via an irrigation system by injecting the chemical into water flowing through the system. This is a relatively new chemical application technology that has numerous advantages which include: (1) increased uniformity of chemical application, (2) prescription application (both timing and quantity) of chemicals, (3) easy chemical incorporation and activation, (4) reduced operator hazards, (5) potential reduction of chemical requirements, (6) potential reduction of environmental

contamination, and (7) cost effectiveness. The disadvantages of chemigation are: (1) requires increased level of management for effective and safe use, and (2) potential for chemical backflow into water supply (Threadgill, 1985).

Groundwater is used as a drinking water source by about 50% of the total U.S. population and about 85-95% of the rural population. Groundwater aquifers contain about 86% of the total water resources in the U.S. (CAST, 1985). Therefore, our current and future dependence upon groundwater is quite substantial, making it one of our most important resources. Contamination of groundwater is a crucial concern throughout the U.S. since contamination can make groundwater unsuitable for human use or for irrigation to produce food, feed and fiber.

Of particular interest in this report is the potential contamination of groundwater by agrichemicals and the effect of irrigation and chemigation on this potential. Agrichemical contamination of groundwater can occur through several mechanisms. The primary mechanisms are: (1) chemicals leaching through the crop root zone into groundwater formations, (2) chemicals being transported by surface flow into "sink holes" which provide a direct conduit for unfiltered surface water to enter aquifers, and (3) chemical backflow into a well.

III. CURRENT STATUS AND TRENDS

IRRIGATION PRACTICES

Irrigation systems can be separated into four categories - surface, sprinkler, subirrigation, and microirrigation. Surface irrigation systems use gravity to distribute water on the soil surface. Land leveling or surface shaping is generally required to achieve the desired uniformity of water

distribution as the water flows either down rows, furrows and corrugations or as the entire soil surface is flooded.

Sprinkler irrigation systems use pressurized pipes to distribute water to sprinklers or nozzles which discharge the water through the air to the plants and soil. The distribution pipes may be either fixed in place or mobile. Sprinkler systems are adaptable to a wide range of soil types and topography.

In subirrigation systems, water is supplied to the crop root zone by raising the water table in the soil so that capillary action can move water upward into the soil root zone. Water is supplied through a system of either unlined surface channels or unpressurized underground pipes. Efficient subirrigation systems require installation on relatively level topography which has an impermeable layer at a depth less than 10 feet below the soil surface.

Microirrigation systems, commonly referred to as either drip or trickle systems, distribute water in closely spaced small diameter pressurized conduits. These conduits may be either above ground, on the soil surface, or buried. Water is distributed from these conduits at low flow rates and low pressures through miniature sprinklers or emitters.

Potential effects of irrigation upon agrichemical contamination of ground-water varies among the four categories of irrigation systems. Deep percolation of irrigation water that transports chemicals below the root zone is much more likely to occur with surface irrigation systems than other types. In most surface irrigation, significant water reaches the lower end of the field. A significant quantity can run off the field and be discharged into surface water resources unless it is blocked or recycled into the irrigation system. This return flow or tailwater, as it is frequently called, can transport chemicals from a variety of sources (e.g. directly added, picked up from soil surface).

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Sprinkler irrigation systems which are installed in areas having high slopes can result in water runoff from the irrigated area if improperly designed or operated. Again, this runoff can contain chemicals from a variety of sources. Subirrigation systems are frequently designed to both irrigate and drain the plant root zone. Although deep percolation should not be a problem in subirrigated areas, any drainage waters could potentially transport chemicals from the field into an offsite drainage system.

The costs of the various irrigation systems are quite variable and depend not only upon system type but also upon soil type, topography, field shape, and water source. In general, capital costs are greatest for subirrigation systems and least with surface systems with sprinkler and microirrigation systems being intermediate. Energy costs are typically highest for sprinkler systems and lowest for surface and subirrigation systems with microirrigation being intermediate. Labor requirements for irrigation systems vary greatly. Systems such as microirrigation and center-pivot sprinkler systems which lend themselves to automation typically have relatively low labor requirements. However, some fixed sprinkler irrigation systems and surface irrigation systems may have relatively high labor costs (CAST, 1988).

Irrigated Area

Irrigation is practiced throughout the United States with acreage varying from only a few hundred acres in some states to over 8,000,000 acres in California. The majority of irrigated acreage (about 85%) is located in the arid, semiarid, and subhumid regions of the seventeen western states. During the period of 1945-1974, the total acreage irrigated in the U.S. steadily increased. The agricultural census tabulated 29.6 million acres of irrigated

land for 1954 and 50.8 million acres for 1978 (U.S. Bureau of The Census, 1982). Hanchar (1989) used unpublished special tabulations from the 1982 census of agriculture to show that total U.S. irrigated acreage remained relatively constant from 1978 to 1982. U.S. Department of Agriculture (1986) data indicate a relatively constant irrigated acreage from 1974 through 1984. Hanchar (1989) also reported that the market value of products sold from farms in 1982 was \$132.3 billion. Of this amount, products from irrigated farms accounted for \$39.7 billion or 30% of the total. Of this \$39.7 billion from irrigated farms, \$26.6 billion were for crops including nursery and greenhouse enterprises while \$13.1 billion were for livestock, poultry and associated animal products. This illustrates that irrigation has a major impact upon U.S. agricultural production with respect to both crops and animals.

The geographic distribution of irrigated farms in the U.S. in 1982 is illustrated in Figure 1 and the geographic distribution of irrigated acreage in 1982 is illustrated in Figure 2. The concentration of irrigated acreage in the seventeen western states, the Mississippi Delta, Florida and South Georgia is evident from these figures. The total irrigated area in the United States essentially stabilized in the 1980's due to low farm commodity prices and increasing irrigation costs, particularly energy related expenses.

Sources of Irrigation Water

Approximately 86% of the total water resources of the contiguous United States are located in groundwater reservoirs or aquifers with the remaining 14% being contained in surface waters (CAST, 1982). Groundwater supplies about 20% of our nation's fresh water and its use is increasing about 4% annually. About 68% of the total groundwater used is applied to crop land by irrigation. About

35% of the water withdrawn for irrigation in the United States comes from groundwater and groundwater supplies about 30% of the streamflow in the U.S. (U.S. Water Resources Council, 1978). Irrigators on the Southern Great Plains depend upon the Ogallala-High Plains groundwater aquifer for about 75% of their irrigation water. Groundwater provides about half of irrigation water used in the central valleys of Arizona and California (CAST, 1988). Therefore, current irrigation practices in the U.S. are very dependent upon the availability and quality of groundwater. Figure 3 shows the location of major groundwater aquifers. Comparison of Figures 1 and 3 illustrates that major concentrations of irrigated acreages are located over major aquifers.

The Irrigation Journal (1982) periodically conducts an irrigation survey which accumulates state-level data on irrigated acreage, acreage irrigated by various types of irrigation systems and irrigated acreage of selected crops. Analysis of the 1982 irrigation survey data indicates that the sprinkler irrigated areas of the U.S. are generally coincident with groundwater aquifers shown in Figure 3.

Hanchar (1989) tabulated that 55.3% of the irrigated acres in the U.S. obtained their irrigation water from wells or groundwater. This groundwater dependent irrigated acreage is concentrated in the principal irrigation states of Arkansas, Louisiana, Florida, Georgia, and the Great Plains states (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma, and Texas) and the minor irrigation states comprised of all those states east of the Great Plains. It should be noted that the majority of irrigated acreage expansion since 1954 has occurred in the Central Great Plains and the Southeastern states (U.S. Department of Agriculture, 1986). Irrigation Journal's irrigation surveys (Irrigation

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Journal, 1982) indicate that sprinkler type irrigation systems have dominated this irrigated acreage expansion.

The information presented above illustrates that the growth of irrigated acreage in the last few decades has relied heavily upon groundwater as the irrigation water source and sprinkler systems as the preferred type of irrigation system.

Management of Irrigation Systems

Effective management of any irrigation system depends primarily upon irrigation scheduling to determine when and how much water to apply. The critical decisions of determining when to irrigate and the amount of water to apply are generally made almost daily during the growing season and are not necessarily independent of each other. The decision about when to irrigate may need to be made several days in advance if the farmer needs to move irrigation pipe, complete other field operations, arrange for labor to irrigate, or relies on an irrigation water supply which requires placing an order for the water. The amount of water to apply depends upon such factors as soil type, stage of crop growth, precipitation since last irrigation or perhaps even precipitation predicted during the next few days, and the probable lapsed time before a subsequent irrigation can be scheduled.

There are three basic methods of irrigation scheduling. These are based upon: (1) allowable soil water depletion, (2) allowable soil water tension, and (3) allowable plant water stress. Scheduling based upon allowable soil water depletion involves irrigating before the water in the plant root zone has been depleted below some predetermined limit. For example, the predetermined limit could be when 50 percent of the available water contained in the plant root zone

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at field capacity has been depleted. The amount of irrigation water to be applied is the amount that has been depleted. Using the allowable soil water tension method, the next irrigation is scheduled to occur before the soil water tension (force required by a plant root to extract water from the soil) reaches a predetermined limit at a specific soil depth. The amount of water to be applied is based upon the relationship between soil water tension and the soil moisture depletion of the soil. The allowable plant water stress method of irrigation scheduling involves measurement of the water stress in some part of the plant and irrigating before that stress reaches a predetermined limit. This method indicates that irrigation is needed but does not indicate the amount of water to be applied.

Proper scheduling of irrigation timing and amount to be applied leads to effective and efficient utilization of our water resources. Improper scheduling can lead to the application of too much or too little water. Overapplication of irrigation water will cause excessive deep percolation of water and associated chemicals or runoff of water and associated chemicals. In the arid parts of the western states where annual rainfall is not adequate to maintain an acceptable salt balance by leaching excess salt below the crop root zone, most irrigation water management practices include some form of salinity control. Irrigation amounts greater than that required for crop growth must be applied to leach the salts from the root zone. This irrigation scheduling to assure deep percolation is essential to the continuation of crop production in these areas. However, it must be recognized that this required deep percolation will also transport chemicals other than salt into the deeper soil profiles with potential transport to groundwater aquifers.

CHEMICAL APPLICATIONS

Agricultural production originally depended almost entirely upon naturally occurring soil nutrients and organic residues derived from agriculture itself. The impoverished soils of low productivity which resulted from this system eventually led to the introduction of legumes to increase the available nitrogen in cropping systems. As plant breeders improved the genetic potential of crop species in response to increased demands for worldwide food supplies, the nutrient requirements of these high yielding varieties greatly exceeded the availability of naturally occurring nutrients. Chemical fertilizers have increasingly been used to supplement the natural supplies of nitrogen and other inorganic nutrients in soils required for plant growth. Similarly, pest control techniques have evolved from the use of natural predators, intensive hand labor and crop rotations to more reliable and less expensive pesticides to insure the consistent availability of high quality agricultural products in sufficient quantities to meet the food and fiber needs of the U.S. and a major portion of the world. Thus, current U.S. agricultural production systems involve the use of fertilizers to supply plant nutrients, inorganic and organic ammendents to improve soil quality, and pesticides to control weeds, insects, and diseases.

These agrichemicals are very important in agricultural production. A wide range of chemical application techniques have been developed for applying various chemicals to specific targets such as plant foliage, soil surface, or incorporation to various depths in the root zone. Current chemical application techniques can be grouped into three categories: (1) ground-based applications, (2) aerial applications, and (3) chemigation.

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Ground-Based Applications

The application of agrichemicals, both nutrients and pesticides, was first done manually either thru hand distribution or hand powered blowers, etc. Animal powered units were later introduced, followed by mechanical powered units in later years. Nutrient sources evolved from animal manure and mineral products to concentrated particulate formulations of single elements and complete fertilizer combinations and now include both particulate and liquid chemical concentrates of single elements and complete fertilizers containing both major and minor nutrients. Nutrients are generally applied by either broadcasting over the entire crop area, banding, or injection beneath the soil surface. In general, a complete nutrient package is distributed prior to primary tillage or crop planting. This is followed in some crops by supplemental applications of selected nutrients during the crop's growing season. A common practice in many regions is the application during the fall of most or all of the plant nutrients for a crop that is to be planted the next spring. In tall growing crops like corn where the operation of tractors during the latter period of the crop growing season can cause significant physical damage to the crop, it is a common practice to apply critical plant nutrients such as nitrogen early in the season although maximum nitrogen needs and uptake by the crop do not occur until some weeks later. Under the conditions just described, mobile plant nutrients such as nitrogen are exposed to the leaching potential of the rainfall and/or irrigation which occurs prior to uptake of the nutrients by the crop.

Some liquid nutrient formulations have been developed for foliar application and foliar uptake by plants. However, the overwhelming majority of plant nutrients are applied to the soil for uptake through plant roots. Plant nutrients applied to the soil must be incorporated into the plant root zone by

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either tillage, direct injection into the soil, or transport with rainfall and/or irrigation water.

Pesticide formulations have evolved from particulates (dusts) to liquid formulations of wettable powders, emulsifiable concentrates, and soluble formulations of pesticides. Ground-based applications of these pesticides have been performed with a wide range of devices. Various applicator designs have been developed to increase uniformity of spray coverage, reduce drift from the target area, increase deposition at desired locations, and reduce the volume of diluent. These devices have included hydraulic sprayers, pneumatic sprayers, airblast devices, large and small propeller driven applicators, spinning cages, and spinning disks. Devices have been developed to produce average spray droplet sizes ranging from a few microns to several hundred microns in diameter. Although numerous devices have been developed for both general and specialty uses, the hydraulic spray nozzle remains the most widely used ground-based chemical application device. Likewise, numerous diluents have been used in ground-based applications, but water remains overwhelmingly the most common diluent. The volume of spray applied per unit area from ground-based units ranges from a few ounces to several hundred gallons per acre. However, the large majority of ground-based application volumes ranges from twenty to forty gallons per acre.

Aerial Applications

One of the relatively early agricultural uses of aircraft was to distribute agrichemicals. Aerial applications of agrichemicals, like ground-based applications, have evolved from primarily dusts to current liquid formulations and have included the development of a wide range of application devices for a broad range of application rates. Both fixed wing and rotary wing aircraft have

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effectively been used for agrichemical applications. A common goal of aerial agrichemical applications has been to achieve effective nutrient distribution or pest control while covering the widest swath using the smallest amount of diluent-chemical mixture.

The drift of aerially applied agrichemicals from the target area has been a major concern. Numerous application devices and special spray additives have been developed to minimize this agrichemical drift from the target area.

Again, similar to ground-based applications of agrichemicals, aerial applications have experienced numerous device and formulation developments which receive some limited use for certain applications. However, the majority of aerial agrichemical applications are still made with the basic technology introduced several decades ago, the hydraulic spray nozzle.

Chemigation

Many irrigators use their irrigation systems to apply agrichemicals. Chemigation, as this practice is commonly called, is defined as the application of a chemical, biological control agent, etc. via an irrigation system by injecting the chemical into the water flowing through the system. Although the term chemigation is relatively new, the concept of applying plant nutrients in irrigation water by simply dumping animal manure into irrigation canals likely began hundreds of years ago. Bryan and Thomas (1958) reported on the basic concept of applying commercial fertilizer through a sprinkler irrigation system over thirty years ago. However, advances in irrigation system design and the availability of chemical injection equipment have now produced the technology for expanding chemigation to include all types of crop inputs. Likewise, new terms such as fertigation, herbigation, fungigation, insectigation, and nemigation have been coined to describe the various types of chemigation. Thus,

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chemigation now encompasses soil applied chemicals, foliar applied chemicals, biological control agents, etc.

During chemigation the chemical reaches only where the irrigation water is applied. Therefore, surface and most microirrigation systems can only be successfully used for chemigation with chemicals that need to be distributed into the soil such as nematicides, most fertilizers, many herbicides, and some fungicides and insecticides. Only sprinkler irrigation systems can be used to apply chemicals to both the soil and foliage. Most insecticides and fungicides, many herbicides such as the recently developed postemergence types, and most growth regulators need to be applied to the plant foliage.

Chemigation with surface irrigation systems is generally considered to be undesirable primarily due to the relatively nonuniform distribution of water characteristic of most of these systems which results in unequal chemical distribution. Also, the environmental damage that can occur when the chemical contaminated tailwater leaves the field is a major concern. If a tailwater reuse system is used, the consequences of the "reapplication" of chemicals contained in the tailwater must be considered. For example, reapplication of tailwater containing excess minerals (e.g. salt), metals (e.g. selenium) or herbicides could result in negative effects on the growth, yield and quality of the crop or toxic effects to birds, animals or humans who consume the crop. However, relatively expensive laboratory tests are usually required to measure levels of potential tailwater contaminants, a factor which basically discourages such testing.

Although it may be technically feasible for subirrigation systems to be used to chemigate highly soluble plant nutrients and perhaps nematicides, chemigation with subirrigation systems is considered to be impractical and basically

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uneconomical due to the relatively large soil volume below the root zone which will unnecessarily be treated with chemicals.

Microirrigation systems which use emitters or porous pipe to distribute water are effective for chemigation of soluble nutrients and pesticides which need to be distributed to the soil. However, microirrigation systems which use miniature sprinklers can be used for chemigation of soluble foliar applied chemicals. A particular constraint on chemigation with any microirrigation system is the very small openings in emitters, minisprinklers, etc. Only soluble chemicals can be successfully transported through these openings, thus limiting the number of chemicals suitable for chemigation through these systems.

Sprinkler irrigation systems, particularly center pivot and linear move systems, are the systems best suited for chemigation. Essentially all types of chemicals and pest control agents can be applied through these systems. By controlling the amount of water applied and selecting the proper formulation, a chemical can be deposited either on the plant foliage, on the soil surface, or distributed to the desired depth within the soil.

Sources of water typically used for irrigation are generally of acceptable quality for effective chemigation. However, it is probable that there could be localized water quality problems such as high mineral content water, very low or very high pH, or very low water temperature that could negatively impact the efficacy of chemigation. However, no definitive data are available on this topic.

The minimum equipment required for chemigation is an irrigation system, an irrigation pumping station, a chemical injection pump, and a chemical reservoir. However, chemigation should never be attempted with only this minimum equipment. Installation and proper maintenance of safety equipment to prevent backflow of

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chemicals into the water source or backflow of water into the chemical reservoir are essential. Liability and potential litigation resulting from inadequate safety equipment or improper use of chemigation is generally recognized (Davis, 1981).

Chemigation is subject to one or more local, state, and federal laws and regulations. Local regulations are usually imposed according to local plumbing codes when public water supplies are utilized for irrigation/chemigation. In some instances irrigation, groundwater, or natural resource districts may have specific chemigation regulations. At least fourteen states have developed laws and regulations pertaining to proper chemigation components and their installation, maintenance and operation to prevent backflow of the chemical into the water source, backflow of water into the chemical reservoir, and chemigation system operator exposure. While these laws in some states apply only to pesticides, most apply to both fertilizers and pesticides. Several other states are considering appropriate legislation. Some examples of state legislation can be found in Georgia, 1981; Wisconsin, 1979; and Florida, 1984. Responsibility for enforcement of these laws and regulations is usually assigned to the state agency responsible for natural resource or environmental protection (e.g. state EPA or DNR).

Several federal acts apply to chemigation. The Federal Insecticide, Fungicide, and Rodenticide Act (FIFRA) requires that pesticides be used as directed on the label and that the purchaser of a pesticide be a certified pesticide applicator or be supervised by a certified applicator. The label on a pesticide container is a legal document having the same force as federal law. The U.S. Environmental Protection Agency, which is responsible for enforcing FIFRA, recently developed a Label Improvement Program (LIP) providing specific

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guidelines for pesticide products used for chemigation. Two key requirements under this LIP are: (1) the pesticide manufacturer must state on the label whether they intend for the pesticide to be applied via chemigation, and (2) approved chemigation system components including those for chemical backflow prevention are listed along with guidelines for their installation, maintenance and operation. Any pesticide applied via chemigation is regulated under this LIP. However, this LIP does not apply to fertilizer products applied by chemigation.

Prior to the development of EPA's LIP on chemigation, any pesticide approved under FIFRA regulations for application to a crop by any application technique could also be applied at the recommended rate by chemigation. Prior to the LIP, pesticide manufacturers' did not have to indicate whether the pesticide was intended to be applied via chemigation. However, implementation of the LIP which required manufacturers to indicate if the pesticide was intended to be applied by chemigation has caused some pesticide manufacturers to state on the label of certain pesticides that they are not intended for chemigation application. Although the full impact of the LIP upon the availability of pesticides approved for chemigation applications is unknown, the implementation of the LIP has certainly resulted in a reduction in the number of pesticides available for chemigation.

The lack of inclusion of fertilizer products in the EPA's LIP leaves chemigated fertilizers unregulated at the federal level. As discussed in later sections, fertigation is the most widely used form of chemigation and nitrate fertilizer contamination of groundwater is a major concern. Therefore, it would appear to be highly desirable to develop an LIP for fertigated products. However, fertilizer products applied via chemigation are regulated under most

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of the state level legislation and regulations, thereby affording some protection.

The American Society of Agricultural Engineers (ASAE) has developed an Engineering Practice, EP409, which describes components of a chemigation system and presents an arrangement of these components which comprises a functional system for minimizing potential environmental contamination and maximizing operator safety (ASAE, 1989).

The Association of American Pesticide Control Officials (AAPCO) has approved a model regulation to help states in the formulation of state laws and regulations concerning chemigation. The AAPCO model regulation stipulates chemigation system components, arrangement, operation, etc. very similar to those described in the ASAE Engineering Practice EP409 and the EPA's LIP under FIFRA (Delaney, 1986).

Other federal laws that pertain to chemigation are the Federal Water Pollution Control Act which deals mainly with surface water and the Federal Safe Drinking Water Act which applies when an irrigation well situated in close proximity to a municipal water well is used for chemigation.

As a result of the development of standards, regulations and guidelines by several professional societies, states, and the U.S. EPA, a notable consensus on appropriate chemigation system components to achieve maximum practical prevention of chemical backflow into water sources has been achieved. Thus, the equipment considered essential for safe chemigation is an irrigation system and irrigation pumping station, a chemical injection pump, a vacuum relief valve, a check valve, an inspection port and low pressure drain in the irrigation mainline, a check valve and a normally closed (hydraulic, solenoid, etc.) valve in the chemigation injection line, and an interlocked system between the power

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supplies for the irrigation pump and the chemical injection pump. These chemigation system components are commercially available in a range of sizes from a variety of manufacturers. Information describing the proper arrangement, installation, maintenance and operation of these components is readily available from component manufacturers, EPA regulators, State Departments of Agriculture, Extension Service personnel and consultants.

Chemigation costs. The potential cost of a particular application via chemigation depends upon the need for supplemental water at the time of chemigation. For example, application of some chemicals may be required at the same time that the crop normally receives irrigation, while other chemical applications may be needed when irrigation is not required by the crop. The latter case will require that the irrigation system be operated just for the purpose of chemigation, resulting in accrual to chemigation of the total cost of that particular operation of the irrigation system. Also, the cost of chemigation will depend upon the amount of water required for an efficacious application of the particular chemical. An additional factor is the capital cost of the chemigation system components. Threadgill (1985) presented a comparison of costs for a single chemigation or conventional (aircraft or tractor sprayer) application of various classes of chemicals. These cost comparisons are presented in Table 1. The costs in Table 1 show that use of a chemigation system for only one chemical application per year will likely be cost effective for only those chemicals requiring incorporation into the soil. Table 2 presents cost comparisons among several scenarios of multiple annual chemigations. It is evident from these comparisons that chemigation is very cost effective when a system is used two or more times annually with chemigation costs ranging from 50 to 87 percent of conventional costs.

Effectiveness. The effectiveness of chemigation has been proven during more than fifteen years of research and practical use on a wide variety of both agronomic and horticultural crops. This effectiveness has been demonstrated with fertilizers, herbicides, nematocides, fungicides, insecticides, broad spectrum soils fumigants, plant growth regulators, and biological pest control agents. Certainly all available chemicals have not been evaluated for use by chemigation. However, to achieve an effective chemigation, it is essential that the irrigation system and chemical injection system be properly installed, calibrated, and operated and that the chemical, chemical formulation, and amount of water applied are also correct. A good selection of reports of chemigation effectiveness can be found in Johnson, et. al. (1986); Phatak (1985); Young (1981); and Young and Sumner (1982). Rather than summarizing the results of all these studies herein, some factors of particular importance to any future expansion of chemigation usage and potential agrichemical contamination of water resources will be described.

Chemical formulation appears to be particularly important for applications where the chemical must be retained on the foliage as is the case with many fungicides, insecticides, postemergence herbicides, and plant growth regulators. In such cases, the most consistent results have been obtained when the technical chemical has been formulated in an oil without the addition of any emulsifier. Wettable powder, water soluble, and emulsifiable concentrate formulations of these foliar active materials have given inconsistent and erratic results in a wide range of tests. This may change when more appropriate technical formulations become available. A great deal remains to be learned about the best formulation of many chemicals when applied by chemigation.

Most evaluations of chemigation have been made at currently recommended rates of the chemical. However, there appears to be considerable potential for increasing yields, reducing chemical rates, or reducing the frequency of application at recommended rates. Young et al. (1984) showed that significant potential exists for reducing total quantities of insecticides required when applied via chemigation. Their chemigation studies on field corn demonstrated an increase in fall armyworm mortality from 50 percent with an emulsifiable concentrate of an insecticide formulated with water to 94 percent when the same rate of the technical insecticide was formulated in oil. This 88 percent increase in mortality resulted from using a formulation designed specifically for chemigation, a formulation which significantly increased the retention of the insecticide on the plant foliage. In a subsequent study, Young et al. (1984) used this increased mortality result to demonstrate that only 5 applications of a technical insecticide formulated in oil were as effective in controlling heavy fall armyworm infestations as 12 applications of the same rate of emulsifiable concentrate insecticide formulated in oil. This represents a 58 percent reduction in insecticide requirements due solely to proper formulation for chemigation. Additional research by Young et al. (1984) on cotton insect control showed that the quantity of insecticide applied could be reduced by 58 percent without a reduction in degree of insect control or crop yield when the insecticide was formulated specifically for chemigation.

In an extensive field study with center pivots in Nebraska, Larson (1984) reported excellent European corn borer control with only one-half recommended rates of an insecticide when applied via chemigation. In a related study, an insecticide formulated in oil for chemigation applied at one-half recommended rate achieved 90 percent average insect control while the standard formulation

applied at recommended rate with a tractor sprayer resulted in only 72 percent average insect control. Similar advantages were tabulated for chemigated insecticides as compared to aerial applications.

Dowler et al. (1982) found that standard formulations of certain herbicides gave significantly better weed control, 88-95 percent vs. 30-70 percent, when applied by chemigation as compared to a conventional tractor boom sprayer, respectively.

Gascho and Hook (1985) showed that corn yields could be increased by applying nitrogen (N) to field corn via chemigation in four applications. They also noted that frequent applications of small quantities of N, a technique facilitated by chemigation, on sandy soils could reduce the leaching of N from the root zone during periods of excessive rainfall.

Management of Irrigation/Chemigation Systems. Since chemicals applied via chemigation are transported by the irrigation water, the uniformity of chemical distribution is very dependent upon the uniformity of irrigation water application. Producers who use chemigation as their chemical application technique must recognize this irrigation/chemigation uniformity interdependency and decide if the chemical application uniformity will be sufficient to meet crop nutrient needs, achieve desired pest control and minimize potential for environmental contamination.

The scheduling of a chemigation application generally coincides with a required irrigation of the crop, but a required chemigation may be scheduled when irrigation is not needed such as in a humid region when sufficient rainfall has occurred to eliminate the need for an irrigation but insects still need to be controlled. In most situations where only chemigation is required, the chemical is applied with the minimum quantity of water that the irrigation

system is capable of distributing, usually less than 0.25 inch of water with sprinkler systems.

A major advantage of chemigation is that chemicals can be applied during inclement weather or at night when application by either aerial or ground-based sprayers is not practical. This prescription application of chemicals offers potential for greatly increased effectiveness and efficiency of both nutrients and pesticides. The net result can be improved crop yields and product quality and/or reduced chemical requirements.

A major concern during either ground sprayer or aerial application of chemicals is operator exposure to the chemicals. One particular advantage of chemigation as compared to other chemical application techniques is that the operator does not have to be exposed to the chemical during its application. A chemigation system does not require constant operator monitoring although periodic monitoring is advised to insure that the system continues to operate properly.

A second major concern during either ground sprayer or aerial application of chemicals is the drift of chemicals from the target area. Drift of agrichemicals applied via chemigation can only occur when applied by sprinkler irrigation systems. There are no reported definitive studies on drift of chemigated chemicals. However, Kohl and Kohl (1985) reported that long distance drift and evaporation of sprinkler chemigated materials are probably less than with ground-based or aerial applications. There have been no reported drift problems with chemigation. After more than a decade of intensive chemigation research and discussions with many research and extension personnel and farmers who have experience with chemigation, the drift of chemicals applied via chemigation does not appear to be a problem with sprinkler irrigation systems

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under wind velocity conditions of less than 8-10 mph (Young and Threadgill, 1984). However, additional information on this subject would be useful.

Another requirement of EPA's LIP on chemigation is the posting of areas to be chemigated if those areas are located within certain distances of designated sensitive areas. The LIP stipulates the wording and letter size on signs as well as the location of signs relative to the chemigated area.

Chemigated Area. The management advantages, positive economics, and effectiveness of chemigation coupled with the rapid development of research information on chemigation during the late 1970's and 1980's stimulated a very rapid increase in the utilization of this crop production management tool throughout the United States. Threadgill (1985) reported the results of a chemigation survey based upon 1983 information. The survey revealed that: (1) 18% of the total 1983 U.S. irrigated acreage was chemigated at least one time, (2) 84% of the total chemigated area (10.6 million acres) in the U.S. was chemigated with sprinkler irrigation systems, (3) 43% of the sprinkler irrigated area, 61% of the microirrigation area and only 3.5% of the surface irrigated area was chemigated at least one time in 1983. Types of chemigation arranged in order of decreasing use were fertigation, herbigation, insectigation, fungigation, and nemigation. Fertigation with sprinkler irrigation systems was the dominant use of chemigation in 1983 and it probably maintains a similar position today. For example, Drablos et al. (1989) reported that as many as 80 percent of Illinois center-pivot irrigators who grow corn apply nitrogen via chemigation. However, insectigation with sprinkler systems has experienced tremendous growth during the past six years (J.R. Young, 1989, personal communication).

Although it is desirable to know the trends in the use of chemigation with respect to geographic distribution, acreage, and type of chemigation, there are

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no reported national level data prior to the 1983 survey nor any subsequent survey data to compare with the 1983 results. Threadgill (1985) estimated that the U.S. chemigated area was increasing at that time at an annual rate of 8 to 9 percent. Applying the 9% annual expansion rate to the 10.7 million chemigated acres in 1983 would result in an estimated U.S. chemigated area of 17 million acres in 1989 or 34% of the total estimated 1989 U.S. irrigated area.

GROUNDWATER QUALITY ISSUES RELATED TO IRRIGATION AND CHEMIGATION

Groundwater is the water that occurs in the earth below the depth to which water will rise in a well. Pore spaces between the solid particles below this depth are filled or saturated with water. Above this depth the soil and other consolidated materials contain some water but is not filled with water. Therefore, it is referred to as the unsaturated zone. Water must move down through the unsaturated zone before it reaches the saturated zone where it becomes groundwater.

The depth to groundwater ranges from only a few feet below the soil surface to several hundred feet depending primarily upon the geology of the earth. As water moves down through the unsaturated zone, it will carry dissolved materials downward from the soil surface to groundwater. Transit time for this water and dissolved materials may be only a few days in some humid areas when the saturated zone is close to the surface, the soil is very permeable to water and substantial precipitation occurs, but it may be measured in centuries in arid regions. Irrigation has the potential to greatly hasten this downward movement if excessive deep percolation occurs.

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Types and Associated Pathways for Groundwater Contamination

The two primary pathways for agrichemical contamination of groundwater are (1) groundwater recharge by either water percolating through agricultural lands or surface flow from agricultural lands and (2) chemical backflow into wells.

Groundwater recharge. In general, water that is supplied to the soil by either precipitation or irrigation will either (1) run off the land surface as overland flow into streams, lakes, or oceans, (2) enter the soil and be returned to the atmosphere by evapotranspiration, (3) flow underground at a shallow depth and reappear as flow in streams, and (4) move downward to recharge groundwater aquifers. Water that moves into surface streams or downward to groundwater will transport dissolved materials including some agrichemicals. It is important to note that in some areas groundwater aquifers intercept surface streams with water usually flowing from the aquifer into the stream. However, if groundwater in the aquifer is sufficiently depleted, water can flow directly from the stream into the aquifer, transporting dissolved materials with it.

The hydrogeologic processes whereby water moves into and through the soil are very complex. This complexity leads to both seasonal and regional variation in the amount of water and dissolved materials that enter the soil and eventually recharge the groundwater (Freeze and Cherry, 1979; Pettyjohn, 1982). The amount of recharge, depth to the water table and fluctuations in depth to the water table vary regionally in response to variations in climate, soils, topography, and geology. In general, groundwater recharge occurs almost every year in humid and subhumid regions if "normal" rainfall occurs during the year. On the other hand, in the semiarid and arid regions of the West, groundwater recharge is usually rather limited and in some years none occurs. In these arid and semiarid areas, groundwater recharge can be quite seasonal tending to be greater during

wet or cool seasons and less during dry or hot seasons. Considering all these variable conditions, groundwater recharge can vary from quite negligible amounts up to perhaps 50% of precipitation (CAST, 1985).

The interaction between groundwater and surface waters in streams and lakes is quite significant when considering potential for agrichemical contamination of groundwater. In humid and subhumid regions, the depth to groundwater is frequently in the range of five to thirty feet below the surface. Under these conditions, most water tables are higher than the streams and lakes. Therefore, groundwater frequently flows into surface waters in streams and lakes. In contrast, the depth to groundwater in arid and semiarid regions is generally quite large such as one hundred to several hundred feet deep (CAST, 1985). Thus, water tables in these regions are frequently lower than the streams and lakes. Therefore, surface waters in the streams and lakes recharge the groundwater. Thus if the surface waters in arid and semiarid regions are contaminated by agrichemicals contained in tailwater from irrigated areas, these agrichemicals can be transported directly into groundwater by the surface water recharge. In contrast, agrichemicals contained in runoff from excessive precipitation in humid and subhumid regions typically remains in the stream flow rather than going directly into groundwater (CAST, 1985). However, there are exceptions that exist in both regions. A particular exception occurs in Karst regions which have irregular topography with "sink holes" on the surface and caverns or underground conduits which result from dissolution of the underlying limestone or carbonate rocks. These sink holes frequently form closed surface depressions, collecting surface drainage or even occasionally entire streams and transporting the water and any dissolved chemicals into the groundwater (Thornbury, 1969; Hallberg and Hoyer, 1982). Consequently, groundwater aquifers in Karst regions are highly

susceptible to contamination by surface runoff. These formations exist under extensive important agricultural areas in the U.S. ranging from Minnesota to Florida and New Mexico to Pennsylvania (Lagrand and Stringfield, 1973).

The movement both water and chemicals thru the soil is quite dependent upon soil characteristics. Three major soil characteristics which significantly affect chemical movement are texture, permeability, and organic matter. Soil texture is an indication of the relative proportions of sand, silt, and clay in the soil. Coarse sandy soils generally allow water and transported chemicals to move rapidly downward and offer few opportunities for chemicals to be adsorbed onto soil particles. Finer textured soils generally allow water to move at much slower rates and they contain more silt and organic matter to which pesticides and other chemicals may be adsorbed. Pest control materials tend to be adsorbed primarily on clay and organic matter. Soil permeability is a general measure of how fast water can move downward in a particular soil. The permeable soils must be carefully managed to prevent chemicals from reaching groundwater. Soil organic matter influences how much water the soil can hold before downward movement occurs. The water capacity of the soil increases with increasing organic matter. Some chemicals, particularly some pesticides, may be adsorbed onto organic matter.

As dissolved chemicals move with water through soil, certain chemicals may be (1) adsorbed onto the surfaces of soil particles and thus removed from solution, (2) transformed into different chemical compounds which may have a greater or lesser contamination potential as their transport continues, and (3) degraded or decomposed into basic elements which are not considered to be contaminants. Most fertilizer chemicals are adsorbed to soil particles and thus do not have a major potential for agrichemical contamination of groundwater.

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However, nitrate and chloride are not appreciably adsorbed and thus move relatively freely with soil water (CAST, 1985). Many pesticides are adsorbed primarily by soil organic matter and consequently pesticide transport to groundwater can be significantly restricted in soils having a high content of organic matter (Green, 1974).

Pesticides are frequently broken down as they move with water through soil. This degradation occurs at different rates but the breakdown does reduce the downward transport of the original substances through the unsaturated zone. It is generally considered that if 50% of a pesticide degrades or decomposes within a few weeks or less, it will usually disappear before reaching groundwater aquifers (CAST, 1985). Obviously, the rate at which water transports a pesticide through the unsaturated zone has a major effect on the pesticide's potential as a groundwater contaminant.

Chemical backflow. Chemical backflow is a second primary pathway for agrichemical contamination of groundwater. Chemical backflow can occur during: (1) the filling of chemical tanks on ground-based or aerial sprayers, or (2) chemigation. Water from wells is frequently used as a diluent in spray tanks on ground-based or aerial sprayers. This water is added to the spray tank either through a direct connection or by a hose. If the water pump in the well malfunctions during filling of the spray tank, a sudden pressure drop could occur, causing chemical or chemical-water mixture to be siphoned back into the well. This backflow can be easily prevented if: (1) a direct connection is not used, (2) the hose end is not allowed to be beneath the water level in the tank, or (3) an appropriate backflow prevention system is installed on the water supply line.

As described earlier, one disadvantage of chemigation is the potential contamination of the water source if proper antipollution or backflow prevention

devices are not in place. There are at least three possibilities for contamination. First, the chemical injection system could shut off unexpectedly while the irrigation pumping plant continues to operate. This could cause water to flow back through the chemical injection system and overflow the chemical supply tank. This overflow of the chemical concentrate or mixture could result in surface water contamination due to surface runoff or groundwater contamination due to leaching. The second possibility is that the irrigation pumping plant could shut off and allow a portion of the water and chemical mixture contained in the irrigation piping to flow back into the irrigation water supply. The third possibility is flow of the concentrate or chemical mixture from the chemical supply tank to the irrigation water source following shutoff of the irrigation pumping plant. This potential agrichemical contamination of water sources during chemigation is well recognized and has been appropriately addressed by the development of numerous state and federal laws and regulations and professional society standards.

Amount and Distribution of Contamination.

Considering all the factors that affect the potential for groundwater contamination by agrichemicals, the primary factors that increase groundwater aquifer vulnerability include intensive cropping, high levels of fertilizer and pesticide use, permeable soils and subsoils, and shallow water tables. Of course, improper irrigation practices can increase this vulnerability. Nielsen and Lee (1987) combined the data associated with these physical contamination vulnerability factors with the limited available data on actual levels of agrichemical contaminants in groundwater. Using this information, they developed estimates of the areas of potential groundwater contamination from both nitrates

and pesticides in the United States (Figure 4). They estimated that the groundwater resources of 46% of the counties in the coterminous United States have a potential for contamination from either pesticides or nitrate fertilizers. Significant areas are subject to potential groundwater contamination from either nitrates only or pesticides only while a more limited area is subject to contamination from both chemicals. Potential groundwater contamination from agrichemicals is generally distributed throughout in the Great Plains, the Upper Midwest, the Lake States, the Eastern Seaboard, and the Gulf Coast with more localized potential in the Western States (CA, AZ, WA, MT). It should be noted that: (1) these are the same areas that have experienced the majority of irrigation acreage expansion in the last few decades, and (2) sprinkler irrigation systems appear to be the dominant type of irrigation system used in these same areas (see discussion in previous sections).

Nielsen and Lee (1987) used 1980 census data to determine that more than fifty million people in the potential groundwater contamination regions illustrated in Figure 5 rely on groundwater for their drinking water needs. Nineteen million of these people obtain their water from private wells, wells which may be more vulnerable to contamination than regulated public system wells. Since most of these private wells are likely to be farmers' wells, agrichemical contamination of groundwater probably affects the farm well first and most directly.

In a summary of nitrogen contamination of groundwater, CAST (1985) notes that nitrate contamination of groundwater at concentrations above the public health standard of 10ppm has been measured in the Cornbelt, the Great Plains, the East, the Southeast, and the West Coast. Nielsen and Lee (1987) analyzed USGS data to develop a geographic distribution of groundwater contamination by

nitrate-nitrogen at moderate (3.1 - 10 ppm) and high (>10 ppm) concentrations. Their results are shown in Figure 6. It is important to note that the USGS data used in Figure 6 do not delineate the source of the nitrates. Nielsen and Lee (1987) note that although many of these nitrate sources have been linked to agricultural practices, some likely result from naturally occurring accumulations (e.g. in the Great Plains and the Southwest).

Although significant data appears to be available describing nitrate concentrations in groundwater, only limited definitive data are available describing the amount of pesticide contamination in groundwater. According to an Environmental Protection Agency official, as many as fifty of the more than one thousand registered pesticides possess the potential for detection in groundwater under conditions conducive to downward movement (CAST, 1985). Based upon a 1984 listing, twelve of these pesticides have been detected in drinking water wells but the concentrations of several were less than the health advisory concentration levels (Cohen, et al., 1986).

In a 1988 report, U.S. Environmental Protection Agency (1988) data show that eighteen pesticides have been confirmed as occurring in groundwater and caused by agricultural practices at levels equal to or greater than health advisory concentrations. This report notes that the apparent increase in the number of pesticides contaminating groundwater could reflect the fact that more people are now looking for pesticides in groundwater and the results merely reflect increased monitoring efforts. The report also discusses the discrepancies between EPA's 1988 data and several other recent assessments of pesticides in groundwater in the U.S. It concludes that the discrepancies are based on the variations in data available at the time of the assessments and in the data collection and interpretation procedures. For example, some pesticide detections

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in groundwater reported earlier as being the result of normal agricultural usage have since been verified as resulting from non-agricultural uses (U.S. Environmental Protection Agency, 1988).

The number of pesticides found in groundwater in each state and caused by agricultural practices is presented in Figure 7 (U.S. Environmental Protection Agency, 1988). Twenty-three states have no pesticide occurrences reported, 7 states have only one pesticide occurrence reported, 2 states have only 2 pesticides reported, 7 states have 3-5 pesticides reported, 8 states have 6-9 pesticides reported, and 3 states have 10 or more pesticides reported. These occurrences are concentrated in the Central Great Plains states, the Eastern Seaboard states, Mississippi, and California.

Table 3 summarizes prominent facts about the constituents of principal concern in groundwater underlying cropland, their sources, soil processes affecting the amount moved to groundwater and their tendency to move with percolating water.

Conventional vs. Conservation Tillage.

Conventional or clean tillage involves plowing under any crop residues and disking or otherwise plowing the soil surface preparatory to planting. Conservation or reduced tillage involves a combination of tillage practices which allows a significant portion of crop residues to remain on the soil surface. In recent years, conservation tillage has been promoted extensively because of its proven benefits in reducing soil erosion and runoff as compared to conventional tillage. Just as conservation tillage reduces runoff and soil erosion, it increases the proportion of precipitation or irrigation water that enters the soil with a corresponding increase in potential water and dissolved

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chemical percolation and leaching. Conservation tillage has been promoted primarily in humid and subhumid regions where excessive precipitation frequently occurs. The increased potential for percolation and leaching of chemicals under conservation tillage systems may result in greater transport of agrichemicals to groundwater than occurs with conventional tillage (Tyler and Thomas, 1977).

The USDA decisions that promote the use of conservation tillage coupled with the compliance provisions of the Food Security Act of 1985 have greatly accelerated the adoption of conservation farming practices. Although conservation tillage practices effectively control soil water and may provide economic benefits, a major national concern is the unknown effect of their expanded use on groundwater quality (U.S. Department of Agriculture, 1989).

Although definitive data are not yet available, it is possible that conventional tillage will be preferred over conservation tillage from the standpoint of potential agrichemical contamination of groundwater. Further research is needed on this subject.

Irrigation Scheduling and System Management.

Table 4 summarizes the behavior of water and pesticides in the atmospheric and soil environments. Since most of the movement of pesticides in soils and underlying materials occurs in conjunction with the movement of water, the parallel arrangement in this table greatly assists in understanding the dependency of pesticide movement on water behavior as water proceeds through various zones. This dependency emphasizes the importance of strategies for managing precipitation, irrigation and drainage waters to minimize the potential for agrichemical contamination of groundwater.

Irrigation scheduling is designed to assure that crops have an adequate supply of water. When irrigation amounts exceed: (1) infiltration rate of the soil, (2) soil water holding capacity, or (3) crop water requirements, the excess

irrigation water will either flow off the land surface into streams and lakes or percolate beneath the root zone. Excess irrigation amounts can occur because of poor irrigation system design, poor irrigation scheduling, improper system management, and to avoid the development of soil salinity from the soluble salts left behind when the irrigation water evaporates. Any application of excess irrigation water increases the potential for agrichemical contamination of groundwater because the excess water will transport dissolved chemicals away from the crop root zone. Thus, excess irrigation applications reduce the efficiency of water and chemical utilization by crops and increase environmental loading.

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IV. EXISTING AND EMERGING IRRIGATION/CHEMIGATION TECHNOLOGIES WITH POTENTIAL TO REDUCE POTENTIAL GROUNDWATER CONTAMINATION BY AGRICHEMICALS

New agricultural technologies are developed by public agencies, private industry and farmers themselves. The adoption of new technologies in production agriculture is typically quite slow regardless of the sector which developed the technology. Even the most economically beneficial agricultural innovations have typically taken ten, fifteen, or even twenty years before being widely adopted. For example, hybrid seed corn, rated by many as the most important innovation for improving agricultural production during the last hundred years, required about fifteen years before it was adopted by many corn growers. Many existing technologies for irrigation and chemigation have not been fully or even widely adopted and new technologies are just entering the technology adoption process. Many of these irrigation/chemigation technologies could reduce potential ground water contamination by agrichemicals.

IRRIGATION TECHNOLOGIES

Irrigation technology has undergone rapid development and change during the past few decades. These changes have included refinements to older irrigation techniques, development of innovative new irrigation systems (e.g. center pivots and trickle irrigation) and scheduling techniques. Technologies for improved scheduling of irrigation applications and improved uniformity of water distribution from irrigation systems appear to offer significant possibilities for reducing potential groundwater contamination by agrichemicals.

Irrigation Scheduling.

Proper irrigation scheduling will provide adequate water for achieving the desirable level of crop yield and quality while minimizing water and dissolved

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chemical runoff and deep percolation, thereby reducing the potential for groundwater contamination by agrichemicals. Proper irrigation scheduling includes a combination of both timing and amount to be applied. The three basic irrigation scheduling methods of allowable soil water depletion, allowable soil water tension, and allowable plant water stress were described earlier in this report.

Most older, conventional methods of irrigation scheduling were based upon convenient times of the day or the relative availability of labor. For example, it was relatively simple for a farmer's children to move irrigation pipe before and after school or for an employee to turn on and off a sprinkler irrigation system on a weekly or a 10-day schedule. However, such techniques do not account for variations in soil characteristics, stage of crop growth or rainfall. Modern irrigation scheduling technology is far more complex than these earlier simple systems. A farmer must either understand how to make estimates or measurements of soil water and plant water use or obtain the use of a consultant.

Visual observation of a crop, probably the original scheduling technique, often indicates plant water stress. However, plants have usually experienced significant reductions in yield or quality by the time plant water stress becomes visible. Therefore, although visual observation may be a simple irrigation scheduling technique, it does not usually provide adequate water for desirable crop yield and quality. A recently developed technology for measuring plant water stress is a handheld infrared thermometer which monitors crop foliage temperature relative to the air temperature. The difference in these two temperatures is an indication of the water status of the crop (Clawson and Blad, 1982) and, when interpreted properly, provides advance notice of a crop yield or quality reducing plant water stress. Although techniques for proper

interpretation are not generally available, research efforts will likely produce relatively reliable techniques in the next few years.

Two techniques for using the allowable soil water depletion irrigation scheduling method are: (1) a calculated soil water balance, and (2) a measured soil water content and set point at a predetermined limit. The calculated water balance method uses a water balance equation to estimate current and future soil water depletions and, thereby, to predict the date when the predetermined limit of soil water depletion will occur. The calculated water balance method usually requires the input of meteorological data such as evaporation rate, humidity, wind speed, solar radiation, and maximum and minimum temperatures. The soil water content/set point control method requires measurement of the soil water content in the root zone. Soil water content measurements can be obtained from either actual soil samples, a neutron probe, or soil moisture blocks. Trends in soil water content can be used to estimate when the predetermined soil water depletion limit will occur and, thus, predict when and how much water to apply.

The soil water retention based irrigation scheduling technique requires actual measurement of the soil water tension by an appropriate sensor such as a tensiometer. These devices provide either an electrical or pressure output which is related to the soil moisture tension. Data from these devices can be used to predict when and how much water should be applied by irrigation.

Computers have been widely used for several years to eliminate the tedious record keeping associated with water balance methods (Kincaid and Heerman, 1974). The advent of low cost microprocessor-based computer systems has been coupled with the measurements available from soil moisture sensors such as tensiometers to develop irrigation scheduling systems which automatically control irrigation pumps, valves, etc. Microprocessor advances have allowed very complex irrigation

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scheduling techniques to be translated into practical and economical systems (Burman et al., 1983).

Automated weather data networks (AWDN) which automatically collect hourly weather measurements is another good example of technology which can improve irrigation scheduling. The meteorological information is processed with microcomputers and made available to farmers and farm consultants who have "dial up" capability. The AWDN has greatly increased the availability of reliable and useful weather data on a near real-time basis which can help users make timely decisions.

Obviously, numerous advancements in irrigation scheduling technology have occurred; however, all of them require a much higher level of management expertise than the more conventional irrigation scheduling systems which are based upon visual observations or fixed time and quantity schedules. The adoption of these scheduling technologies has progressed at approximately the normal agricultural technology adoption rate (CAST, 1988). Although scheduling technologies offer potential for reducing groundwater contamination of agrichemicals through a reduction of runoff and leaching, this potential will not be fully realized until widespread adoption of these improved irrigation scheduling techniques is achieved.

Irrigation Application Uniformity.

Nonuniform distribution of irrigation water can result in excessive runoff and percolation of water and dissolved chemicals in those areas of the field where excessive quantities of water are applied. Poor uniformity can occur with any irrigation system but tends to be of primary concern with surface and sprinkler type systems. Recently developed surface irrigation innovations which can increase uniformity of irrigation application and potentially reduce the quantities of tailwater leaving the field include surge flow systems, cablegation

and laser-controlled land leveling. Surge flow systems are applicable to graded furrow type surface irrigation systems. In a surge flow system, an electronic controller operates one or more valves in a surface pipeline tee to apply water in repeated on and off cycles through a gated pipe to a set of furrows on each side of the tee. Research has shown that surge flow is effective in reducing water intake rates and application depths and has reduced deep percolation losses on some soils to about one-third of conventional continuous flow furrow irrigation (Musick, et al., 1985). Combined usage of surge flow systems with tailwater reuse systems offers opportunities for substantial reductions in the runoff and deep percolation of water and dissolved chemicals on moderately permeable soils. However, Manges et al. (1985) found that surge flow is ineffective on silt loam soils while Izumo and Podmore (1984) reported only minor benefits for surge flow on tighter soils or under compacted soil conditions. Musick, et al. (1988) indicated that surge flow systems have been rapidly adopted in the Texas High Plains irrigated area since the introduction of this technology in 1983.

Cablegation is a recent development which automates some surface irrigation systems and improves their performance (Kemper, et al., 1981). In cablegation, a surface pipeline located at the upstream end of a furrowed field contains a plug which moves slowly within the pipeline. The speed of the moving plug is automatically determined by a control mechanism such that water is released to each furrow in sequence and at varying rates from openings in the pipe. Cablegation can reduce deep percolation and tailwater volumes.

The use of laser controls for land leveling equipment has greatly simplified and improved land smoothing and reshaping for surface irrigation systems. Laser controlled land leveling technology has been widely adopted throughout the construction industry. The improved smoothing and shaping of fields for surface

irrigation with laser controlled equipment significantly increases the uniformity of water distribution and thus reduces the potential for deep percolation and tailwater volumes (Dedrick et al. 1982).

A recent development in sprinkler irrigation hardware is the low energy precision applicator (LEPA) system, a low energy use adaptation of center pivot and lateral move systems. Drop tubes and orifice controlled emitters or spray nozzles are used to achieve precise control of water application from LEPA units. Very low pressure water is released at or just above the soil surface directly into microbasins in each furrow or alternate furrows. Microbasins are constructed by tillage systems which produce small dikes or dams at intervals of a few feet along each furrow. These microbasins prevent runoff of high intensity irrigation water applications such as occur with LEPA equipment. Combining microbasin tillage systems with a LEPA irrigation system retains the high intensity discharge of water from LEPA unit in the immediate area of application, thereby assuring unusually high uniformity of water application (Musick et al., 1988). LEPA systems have not been evaluated on or adapted to slopes greater than about 5% (Cast, 1988).

Microbasin tillage systems can also be used in combination with conventional sprinkler irrigation systems to minimize or prevent runoff on slight to moderately sloped topography.

CHEMICAL APPLICATION TECHNOLOGIES.

There are some existing and emerging chemical application technologies which directly impact upon potential groundwater contamination by agrichemicals under irrigated systems. These chemical application technologies can be grouped into three categories: (1) ground-based and aerial applications, (2) "piggyback application systems, and (3) chemigation.

Ground-based and Aerial Applications.

Ground-based and aerial chemical application technologies which increase the deposition of chemicals on the plant, increase retention of chemicals on plant foliage or in the soil, or reduce chemical application requirements all have the potential for reducing groundwater contamination by these agrichemicals. Various spray application systems and devices have been developed to achieve one or more of these three advantages. Devices such as air tube sprayers, controlled droplet applicators, ultra-low volume (ULV) devices and electrostatic sprayers have each shown promise of increased deposition on plant foliage and/or reduced chemical application rates required to achieve desired pest control.

Any chemical application technology which reduces the washoff of chemicals from plant foliage or otherwise reduces the quantity of chemicals available for transport in irrigation water will have the potential for reducing potential groundwater contamination by those agrichemicals. Ground-based electrostatic spraying systems have been shown to improve the deposition of pesticides on plant foliage and achieve good pest control with significantly reduced rates of pesticides (Law, 1983). Controlled droplet applicators generate agrichemical droplets of a uniform size. The droplet size is selected to either optimize the control of a selected pest or to achieve agrichemical deposition at a specific target site.

As described in an earlier section in this report, there have been numerous developments in devices and chemical formulations for application of chemicals with both ground-based and aerial applicators. While each of these developments offer specific advantages, none of them have received general adoption. Instead, the most widely used technology has remained the hydraulic spray nozzle.

"Piggyback" Chemical Application.

Piggyback chemical application systems were introduced in the late 1970's. A piggyback system is achieved by attaching an auxiliary agrichemical spray distribution boom on a continuously moving irrigation system such as a center-pivot or a linear move unit. The auxiliary spray boom may be attached alongside of or beneath the main irrigation pipeline. These systems are usually designed to apply a water-chemical mixture at spray volumes up to 100 gallons per acre. Piggyback systems differ from chemigation systems for two reasons: (1) application rates are generally in the range of high volume conventional spray application rates, and (2) agrichemicals are not distributed by injecting them into the irrigation water. Piggyback systems have been presented in two basic designs. In one configuration, the agrichemical spray nozzles are mounted in a stationary position above the crop. In the second configuration, conventional agrichemical spray nozzles are positioned on vertically oscillating drop booms which move the spray nozzles vertically up and down within the crop canopy, distributing agrichemicals at prescribed levels (Lyle and Bordovsky, 1983). This second arrangement is referred to as a multifunction irrigation system (MFIS). Although the MFIS has been called a chemigation system by some (Lyle and Bordovsky, 1988), it is not a chemigation system but is actually a variation of the tractor boom sprayer mounted on a center-pivot or lateral move irrigation system - a piggyback system. Chemicals are not distributed by injecting them into the irrigation water; rather, a separate chemical distribution boom is used for applying chemicals. Installation of an MFIS requires significant capital investment and includes a relatively complex arrangement of pipes, control cables, etc. The MFIS offers the potential for improved deposition and reduced chemical application rates (Lyle and Bordovsky, 1988), thereby offering the same

potential for reducing groundwater contamination as described in the previous section.

Chemigation Technologies.

As discussed in previous sections, chemigation is a relatively new and innovative agrichemical application technology which has received relatively rapid and widespread adoption, particularly with sprinkler and microirrigation systems. Since agrichemicals applied via chemigation are transported by the irrigation water, the interdependency of irrigation and chemigation presents unique possibilities for both positive and negative impacts upon potential groundwater contamination by chemigated agrichemicals. Several existing and emerging chemigation technologies are described in the following paragraphs.

Irrigation systems have been designed for the application of water, not the application of agrichemicals. Chemigation has simply been adapted to existing systems designed for irrigation only. While chemigation without irrigation system redesign has been very successful and effective, there appears to be significant potential for altering the configuration of some irrigation systems to increase the benefits and reduce the potential negative impacts of chemigation (Threadgill, 1985). Any modifications to irrigation systems which will increase the uniformity of agrichemical distribution, increase the efficacy of agrichemicals, or increase the adsorption or retention of agrichemicals on plant foliage or in the soil will reduce potential groundwater contamination by these agrichemicals.

Although limited information is available, some effects of irrigation sprinkler design, pressure and flow velocity within the irrigation main line, agrichemical injection port design and orientation, and agrichemical injection pump characteristics upon agrichemical distribution and efficacy have been observed.

Young and Threadgill (1984) noted that the design and orientation of the agrichemical injection port which disseminates agrichemicals into the irrigation water affects insect control with insectigation of certain insecticide formulations. Cochran et al. (1984) illustrated that irrigation system pressure, chemical injection port orientation, and irrigation sprinkler characteristics definitely affect the droplet size distribution of oil-formulated pesticides. Groselle et al. (1984) and Cochran et al. (1984) found that the irrigation sprinkler will generally reduce the size of oil-insecticide droplets as compared to droplet sizes found in the irrigation mainline flow. Smaller sprinkler orifices caused a greater reduction in oil-insecticide droplet sizes than larger orifices. Groselle et al. (1984) also noted that the pulsation rate of the agrichemical injection pump significantly affects the diameter of oil-insecticide droplets. Young (1989) noted that the efficacy of insectigated agrichemicals is affected by the size of oil-insecticide droplets.

The velocity of flow in an irrigation mainline decreases with increasing distance from the point of agrichemical injection. This results in a decreasing potential for entrainment and mixing of injected materials. While this may be of negligible influence for water soluble formulations of fertilizers (Fischbach, 1982), other results suggest that the distribution uniformity of water soluble herbicides may differ from the uniformity of the irrigation water distribution and that the distribution concentrations and uniformity of these herbicides can be substantially different between high and low pressure irrigation systems (Dowler et al., 1982). Young (1989) noted that the efficacy of oil-formulated insecticides has been erratic and unacceptably low when applied via chemigation in an irrigation system having an initial mainline flow velocity of less than 4.5 feet per second. These results indicate the potential impact of irrigation system and chemigation system characteristics on chemical distribution and

efficacy. The referenced studies and other studies currently being conducted are developing information which will lead to criteria for designing a combined irrigation/chemigation system for optimized application of both water and agrichemicals.

Agrichemical formulations are a second area of chemigation technology which offers a significant potential for reducing potential groundwater contamination by chemicals. Agrichemical formulations which increase the potential for deposition and retention of chemicals at desired locations within the plant canopy or soil provide the opportunity for using reduced rates of chemicals while maintaining adequate efficacy. Several studies have shown that water insoluble but oil soluble insecticides applied by chemigation gave the best control as compared to water soluble or emulsifiable concentrate formulations of the same insecticide (Chowdhury, 1985; Chalfant and Young, 1982; Young et al., 1984). Limited data show that the combination of some technical pesticide formulations with a nonemulsifiable oil will significantly increase the deposition and retention of these pesticides on plant foliage, thereby reducing the amount of chemical that leaves the targeted foliar zone (Stone, 1985). This characteristic suggests that the development of agrichemical formulations specifically for chemigation offers the potential for greatly enhanced deposition and foliar retention which translates into potentially fewer chemical applications and reduced chemical rates per application. The potential combined benefits of formulations specifically designed for chemigation could result in the application of much lower quantities of chemicals per crop per year (Larson, 1984; Young, 1986) and a reduction in the exposure of these chemicals to dissolution in and transport by either precipitation or irrigation water. Current research on chemical formulations is very limited and appears to be concentrated at the University of Georgia.

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Agrichemical manufacturers have been particularly reluctant to allocate resources to the development of agrichemical formulations specifically for chemigation. Their reluctance is probably based upon economic considerations. That is, if a formulation for chemigation actually results in less chemical being required, then the potential sales by the manufacturer could easily decrease, leading to a decline in revenues. The reluctance of private industry to participate in the development of chemigation formulations coupled with the lack of resources and expertise in public agencies for developing these formulations could mean that the potential for reducing potential groundwater contamination from agrichemicals by developing specific chemigation formulations will never be realized.

The versatility in agrichemical application offered by chemigation is another area of significant potential impact upon potential groundwater contamination. Chemigation, unlike other chemical application techniques, can be utilized day or night and during fair or foul weather (chemigation has been effectively utilized during rainfall). Many agrichemicals such as nutrients and some nematicides, herbicides, etc. require water for activation. Likewise, some of these same agrichemicals require incorporation within the soil for optimum plant uptake or pest control. Some of the studies described in previous sections have illustrated that if an appropriate agrichemical formulation is chemigated with an appropriate quantity of irrigation water, the agrichemical can be deposited in the plant canopy, on the soil, or incorporated within the soil as desired. Chemigation is the only chemical application technique that allows this degree of site specific application of agrichemicals.

Integrated Pest Management (IPM) programs combine chemical use with many other production practices to manage pests in ways that are both economically and environmentally sound. IPM programs include use of such practices as crop

rotations, alternate pest control products, pest resistant crop varieties, and careful pest monitoring to insure that chemical control methods are used only when needed. When pest monitoring indicates that a chemical treatment is needed in an IPM program, the timing of that treatment can be critical to the success of the entire IPM program. Inclement weather can prevent timely chemical applications with either ground-based or aerial units but chemigation can be scheduled when needed. Thus, chemigation appears to offer a significant contribution in insuring the success of IPM programs, programs which are specifically designed to minimize the use of agrichemicals and thus minimize environmental loading by these materials.

As described in previous sections, chemigation is subject to one or more local, state, and federal laws and regulations with respect to backflow prevention systems. The components for assembling an appropriate backflow prevention system are commercially available in a range of sizes from a variety of manufacturers. In the past, the irrigator or farmer has been faced with the difficult task of procuring individual components and assembling them into a functional backflow prevention system. Unfortunately, in some cases these components were not properly sized or arranged for optimum backflow prevention. However, several manufacturers have recently developed complete backflow prevention systems with properly sized and arranged components. These systems are sold as a unit and in a range of capacities from which the irrigator can select a unit appropriate for his application. This availability of "standardized" backflow prevention units will significantly enhance the reliability of these systems.

Performance standards and reliability testing procedures for backflow prevention components and complete systems are still lacking. Even greater reliability and standardization of design for backflow prevention components and

systems will be forthcoming when performance standards and reliability testing procedures are developed. The University of Nebraska has recently initiated a limited program directed towards performance evaluation of selected components.

Although chemigation is a recently developed chemical application technique, considerable resources and effort have been devoted to insuring the safe and effective adoption and use of this technology. For example, a Chemigation Safety Conference (Vitzthum and Hay, 1985) was held in 1985, bringing together experts on all aspects of chemigation. Discussions at this conference covered topics ranging from operator safety to backflow prevention systems to environmental concerns. Also, three national symposia on chemigation have provided forums for discussions of current developments in this technology (Young, 1981; Young and Sumner, 1982; and Phatak, 1985). An outgrowth of the Chemigation Safety Conference was the development of two slide-tape sets, one describing chemigation system calibration techniques and the second describing the selection, installation and maintenance of backflow prevention systems equipment. These slide-tape sets have been made available through the Cooperative Extension Service to all county agents in the U.S. who have chemigation usage in their counties. In addition, extensive information is available from Cooperative Extension Service offices, irrigation system manufacturers, and chemigation system manufacturers on the selection, operation, use, and maintenance of chemigation systems and chemigation. A National Information Exchange Group, comprised of representatives from the chemigation equipment and chemical industry, public research/education/service institutions, regulatory agencies, and chemigation users, has been active for several years. This group meets annually, providing an open forum for any interested party to discuss concerns and express needs associated with any aspect of chemigation. Coupling these conferences, symposia, groups, and technology transfer efforts with the extensive

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development of laws and regulations pertaining to chemigation, the tremendous concern for the development of chemigation as an efficacious but environmentally sound technology is evident.

SUMMARY

The discussion in the above paragraphs illustrates that there are significant existing and emerging irrigation/chemigation technologies that have the potential to reduce the potential for groundwater contamination by agrichemicals. In particular, significant advances could be made by the more widespread utilization of advanced irrigation scheduling techniques, the adoption of improved irrigation uniformity technologies, the modification of irrigation system designs to enhance chemigation, the development of agrichemical formulations particularly suited to chemigation, the development of performance standards and reliability testing procedures for chemigation backflow prevention systems, and the exploitation of the agrichemical application scheduling diversity offered by chemigation.

POTENTIAL CONGRESSIONAL POLICY OPTION

ISSUE: REDUCE OR WITHDRAW IRRIGATION SUBSIDIES

Irrigation subsidies could be withdrawn or reduced in regions having a substantial potential for groundwater contamination by agrichemicals. This action would increase the cost of water for irrigation and thereby encourage the adoption of irrigation technologies which allow more efficient utilization of irrigation water. More efficient utilization of irrigation by crops implies that less water will be available for the transport of agrichemicals to groundwater through either runoff or deep percolation.

Irrigation subsidies are utilized in all or part of the 17 western states. In 1976, the Bureau of Reclamation provided the total water supply to 14% of the irrigated lands in those 17 western states and a supplemental supply to about 11%. Therefore, any alterations in irrigation subsidies would affect only a limited portion of the irrigated lands and only in the 17 western states. It is probable that the majority of irrigated acreage receiving subsidized irrigation waters are not located over groundwater aquifers. This is certainly the case in the 11 most westerly of the 17 western states. Therefore, it would appear that reducing or withdrawing irrigation subsidies would impact only a very small percentage of the total irrigation area of the U.S. which has a potential for groundwater contamination from agricultural chemicals.

However, the reduction of potential groundwater contamination by agrichemicals is desirable even in localized areas or on only a small percentage of total U.S. irrigated area. Implementation of the option of reducing or withdrawing irrigation subsidies would likely result in serious economic difficulties for most subsidized irrigators. A viable alternative to reducing or withdrawing irrigation subsidies would be to sell the irrigators' water rights to higher valued, non-irrigator, water users, thereby economically compensating the irrigator while transferring the water use to a use having an assumed reduced or eliminated potential for groundwater contamination.

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POTENTIAL CONGRESSIONAL POLICY OPTION

ISSUE: ENHANCING THE DEVELOPMENT OF CHEMICAL FORMULATIONS SPECIFICALLY FOR CHEMIGATION

The use of Chemigation for the application of agrichemicals with sprinkler type irrigation systems offers the potential for reduced frequency of chemical application or reduced chemical volume per application, either of which will reduce the total quantity of chemicals required for crop production. However, agrichemicals formulated specifically for chemigation are required to realize this potential. Agrichemical manufacturers have been very reluctant to allocate resources for researching and developing these required formulations. Congress could provide economic or regulatory incentives to encourage agrichemical manufacturers to develop agrichemicals specifically formulated to enhance chemigation. The enhanced utilization of chemigation could have a direct and positive impact upon potential groundwater contamination.

Chemigation is a relatively new agrichemical application technology which depends upon irrigation water for transporting and distributing the agrichemicals. An estimated 34% of the 1989 U.S. irrigated acreage was chemigated at least one time with the overwhelming majority of chemigation being conducted with sprinkler irrigation systems. Sprinkler systems are the dominant irrigation system used in areas located over major groundwater aquifers.

Since chemigation is used primarily with sprinkler irrigation systems which are located over major groundwater resources, enhanced usage of chemigation with these irrigation systems offers significant potential for reducing the potential of groundwater contamination by agrichemicals. A major limitation to achieving chemigation's potential for reducing the quantities of agrichemicals required for crop production is the lack of agrichemical formulations specifically developed for chemigation. Although conventional agrichemical formulations have proven to be effective when applied by chemigation, their efficacy has been erratic and inconsistent when applied by chemigation at less than recommended rates. Research has demonstrated that altering the formulation of certain pesticides and applying them by chemigation has allowed the use of significantly reduced quantities of chemical while maintaining desired levels of insect and weed control, and crop yield. However, agrichemical manufacturers have been reluctant to allocate resources to the development of agrichemical formulations specifically for chemigation. Their reluctance appears based on economic considerations; that is, if a formulation for chemigation actually results in less chemical being required, then the manufacturer could easily experience declining sales and thus declining revenues.

Public agencies do not have the resources and expertise required for developing agrichemical formulations specifically for chemigation. Providing appropriate incentives to encourage private industries to participate in the development of chemigation formulations could result in a significant reduction in the quantities of chemicals applied in several major crop producing areas overlying groundwater aquifers. Such developments could significantly reduce the potential for groundwater contamination from agrichemicals in major groundwater aquifer areas of the United States.

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ISSUE: ENHANCING THE DEVELOPMENT OF IMPROVED CHEMIGATION EQUIPMENT

The components for assembling a chemigation system are available but few of them have been specifically designed for chemigation. Therefore, considerable potential exists for improving both the safety and efficacy of chemigation systems through improved equipment design and development. Congress could appropriate funds thru the USDA Competitive Grants Program to public agencies and educational institutions to support research and development of improved irrigation systems for chemigation, chemigation system components and complete chemigation systems. The development and use of more effective and safer chemigation systems would have a direct and positive impact upon potential groundwater contamination.

Irrigation systems have been designed for the application of water, not the application of agrichemicals. Chemigation has simply been adapted to existing systems designed for irrigation only. Likewise, most components of chemigation systems such as injection pumps, injection ports, and backflow prevention devices have simply been adapted from off-the-shelf items with only limited effort to design chemigation systems specifically adapted to chemigation. Chemigation without irrigation system redesign or complete chemigation system design has been successful and effective. However, there appears to be significant potential to increase the benefits and reduce the potential negative impacts of chemigation by altering the configuration of some irrigation systems and designing complete chemigation systems.

Any modifications to irrigation systems which will increase the uniformity of agrichemical distribution, increase the efficacy of agrichemicals, or increase the adsorption or retention of agrichemicals on plant foliage or in the soil will reduce potential groundwater contamination by these agrichemicals. Examples of irrigation system characteristics which appear to affect chemigation include irrigation sprinkler or emitter design, pressure and flow velocity within the irrigation pipeline, distribution uniformity of water and chemicals, and devices to maintain uniform mixing of certain chemicals in the water. Each component of the chemigation system, from the chemical tank to the injection port, likewise needs to be designed for enhanced chemigation as both individual components and as a complete system. Criteria identifying the proper size and arrangement of chemigation system components for optimum backflow prevention are critically needed. Such criteria would enhance the development and use of properly sized and arranged "standardized" backflow prevention units, thereby significantly enhancing the reliability of backflow prevention systems. Programs should be instituted to develop performance standards and reliability testing procedures for backflow prevention components and complete systems.

The development of design criteria for combined irrigation/chemigation systems would be greatly enhanced and accelerated by the provision of competitive grant funds to public agencies and educational institutions via the USDA Competitive Grants Program. Information and criteria developed under such a program would be rapidly transferred to industry through the existing network of industry/public agency/university collaborative research arrangements relative to chemigation. This could lead to more cost effective and safer backflow prevention systems, improved uniformity of chemical distribution, and enhanced efficacy of chemicals applied via chemigation. Each of these factors would have a positive and direct impact upon potential groundwater contamination.

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TABLE 1. Costs of a single chemigation and conventional application of chemicals (from Threadgill, 1985)

Type of Chemical	Conventional ¹ \$/ha	Chemigation ² \$/ha	Water Applied mm
Fertilizer	\$ 6.20	\$ 13.06	10
Herbicide	14.00	13.06	10
Insecticide	5.60	9.84	3
Fungicide	5.60	9.84	3
Nematicide	14.00	13.06	10

¹Costs of aircraft and tractor sprayer assumed to be equal.

²Based upon average operating cost of a 61 ha center pivot (fixed cost of irrigation system charged against irrigation) plus entire annual fixed cost of chemigation system.

³Includes cost of mechanical incorporation.

Table 2. Costs (\$/ha) for Multiple Chemigation and Conventional Applications of Chemicals.

Chemicals and number applied*	<u>1</u> 1F	<u>2</u> 1F, 1H	<u>3</u> 2F, 1H	<u>4</u> 2F, 1H 1I	<u>5</u> 2F, 1H 1I, 1Fg	<u>6</u> 2F, 1H 2I, 1Fg	<u>7</u> 2F, 1H 4I	<u>8</u> 3F, 1H 4I	<u>9</u> 3F, 2H 4Fg	<u>10</u> 3F, 2H 5I
Chemigation										
Fixed cost+	\$8.56	\$8.56	\$8.56	\$8.56	\$8.56	\$8.56	\$8.56	\$8.56	\$8.56	\$8.56
Variable cost++	4.00	9.00	13.50	14.78	16.06	17.34	18.62	23.12	27.62	28.88
Total cost	13.06	17.56	22.06	23.34	24.62	25.90	27.18	31.68	36.18	37.44
Conventional**										
Total Cost	6.20	20.20	26.40	32.00	37.60	43.20	48.80	55.00	69.00	74.60
Chemigation savings -	-6.86	2.64	4.34	8.66	12.98	17.30	21.62	23.32	32.82	37.44

*F = fertilizer, H = herbicide, I = insecticide, Fg = fungicide, numeral indicates number of applications of particular type.

+Assumed \$4,000 fixed cost of chemigation system plus \$2/ha annual maintenance cost.

++Based upon operating cost of a 61 ha center pivot.

**Refer to Table 20.1 for individual values.

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Table 3. Summary of Prominent Facts About the Constituents of Principal Concern in Groundwater Underlying Cropland (From CAST, 1985)

Constituent	Sources	Soil Processes Affecting the Amount Lost to Groundwater	Tendency to Move Downward Through Soils in Percolating Water	Comments
Soluble salts	Irrigation water Organic materials Fertilizers Weathering of soil minerals Rainfall	Precipitation and dissolution of carbonates and sulfates Weathering of soil minerals	High	Must be leached from most irrigated soils to maintain crop production
Nitrate	Nitrogen fertilizers Organic materials Atmospheric nitrogen fixed by legumes Rainfall	Production and removal by microorganisms Removal by plants	High	Loss to groundwater is incidental to water movement and is a loss to crop production potential
Pesticides	Commercial products	Retention by soil Decomposition Volatilization Removal by plants	Varies widely among pesticides and soils	Principal occurrences in groundwater result from pesticides that remain in solution in the soil, are not decomposed rapidly, and are applied to sandy soils with groundwater near the surface and with much water movement through the soil to groundwater

Table 4. Behavior of Water and Pesticides in the Atmospheric and Soil Environments^a

Environment Zone	Water Behavior	Pesticide Behavior
Atmosphere	Addition by evaporation from land and water surfaces, transport by air movement, and sprinkler irrigation Loss by precipitation, transport by air movement, condensation, and sprinkler irrigation	Addition by application, volatilization from plants and soils, and transport by air movement (drift) Loss by deposition on plants and soils, transport by air movement, and decomposition by sunlight
Above-ground crop zone	Addition by precipitation, sprinkler irrigation, and condensation Loss by throughfall, evaporation, and transpiration	Addition by application to foliage and by transport by air movement Loss by volatilization, throughfall, wash-off, and decomposition by sunlight and plant metabolism
Soil surface	Addition by precipitation, lateral movement on the surface, irrigation, condensation, and upward movement from the zones beneath Loss by evaporation, lateral movement on the surface (runoff), and movement into the zones beneath	Addition by application to the soil, transport by air movement, throughfall and wash-off from plants, lateral transport on the surface, and upward transport from the zones beneath Loss by volatilization, lateral transport on the surface (runoff), transport into the zones beneath, and decomposition by chemical and biological means Retention by the soil
Root zone (unsaturated soil)	Addition by movement from the soil surface and zones beneath Loss by uptake by roots and movement to the soil surface and the zones beneath	Addition by subsurface application and by transport from the soil surface and zones beneath Loss by decomposition by chemical and biological means, by uptake by roots, and by transport to the soil surface and the zones beneath Retention by the soil
Unsaturated zone below root depth	Addition by movement from the zones above and beneath Loss by movement into the zones above and beneath	Addition by transport from the zones above and beneath Loss by decomposition by chemical and biological means and by transport into the zones above and beneath Retention by the soil
Saturated zone (groundwater)	Addition by movement from the zones above and by lateral and vertical movement within the saturated zone Loss by movement into the zones above and by lateral and vertical movement within the saturated zone	Addition by transport from the zones above and by lateral and vertical transport in groundwater Loss by transport into the zones above, by lateral and vertical transport within the saturated zone, by discharge to bodies of surface water, and by decomposition by chemical and biological means Retention by the soil

^a This table is a modified version of one prepared by R. E. Green and N. P. Kefford, University of Hawaii. (CAST, 1985)

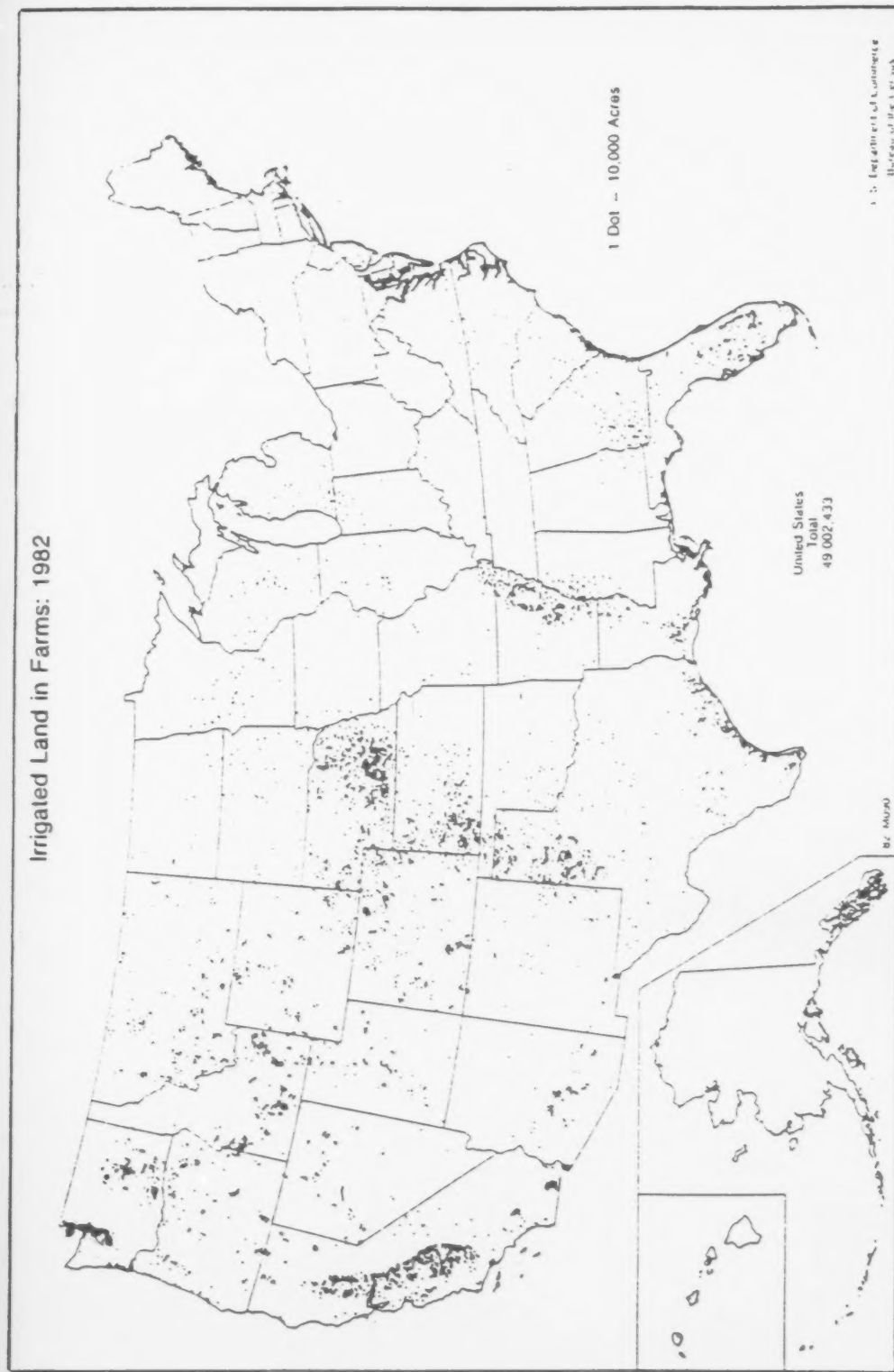


Figure 1. Irrigated Land in Farms: 1982 (U.S. Department of Commerce, 1985).

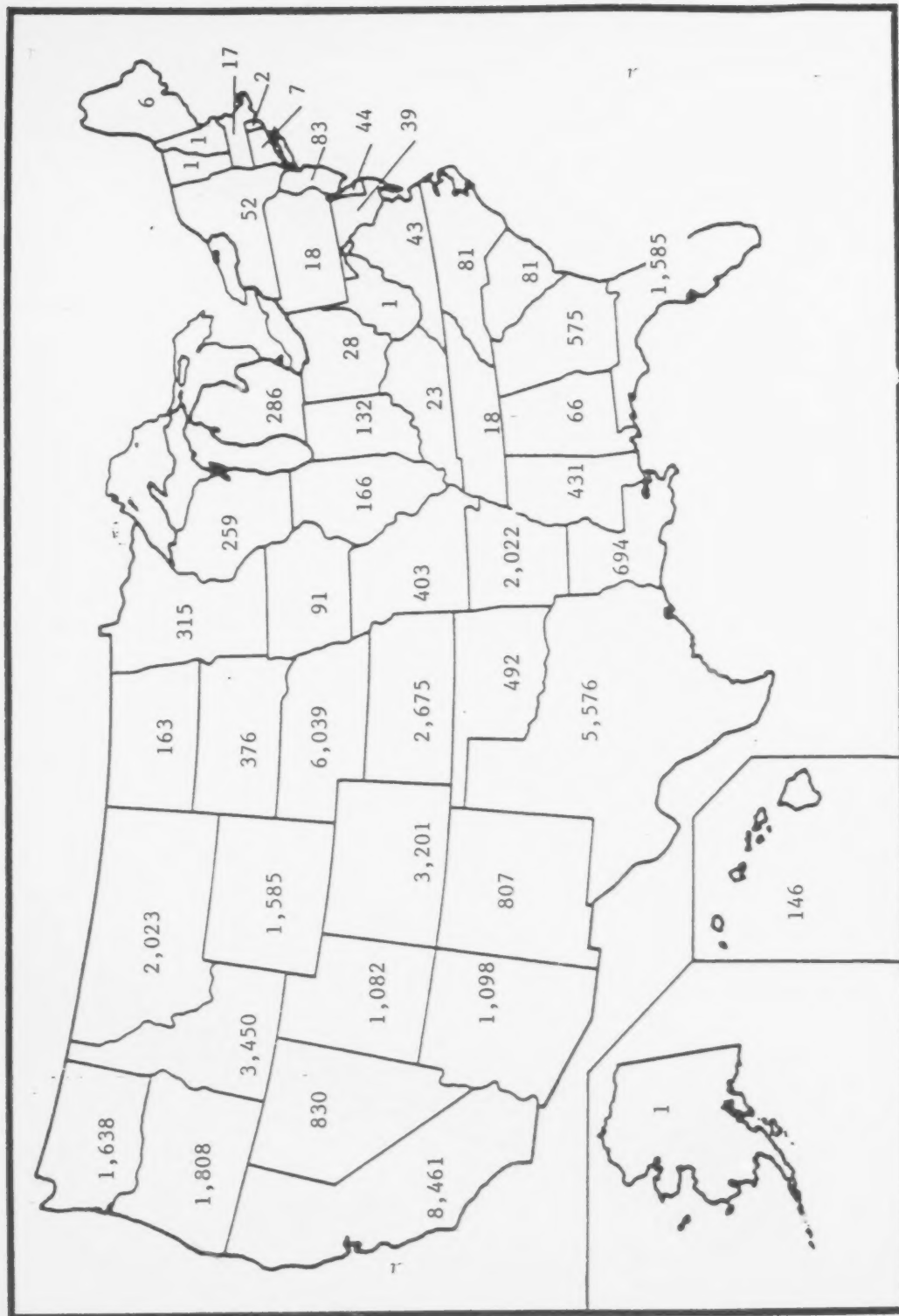


Figure 2. Areas of Irrigated Land in the United States in 1982.

Numbers are Thousands of Acres. (U.S. Department of Agriculture, 1986)

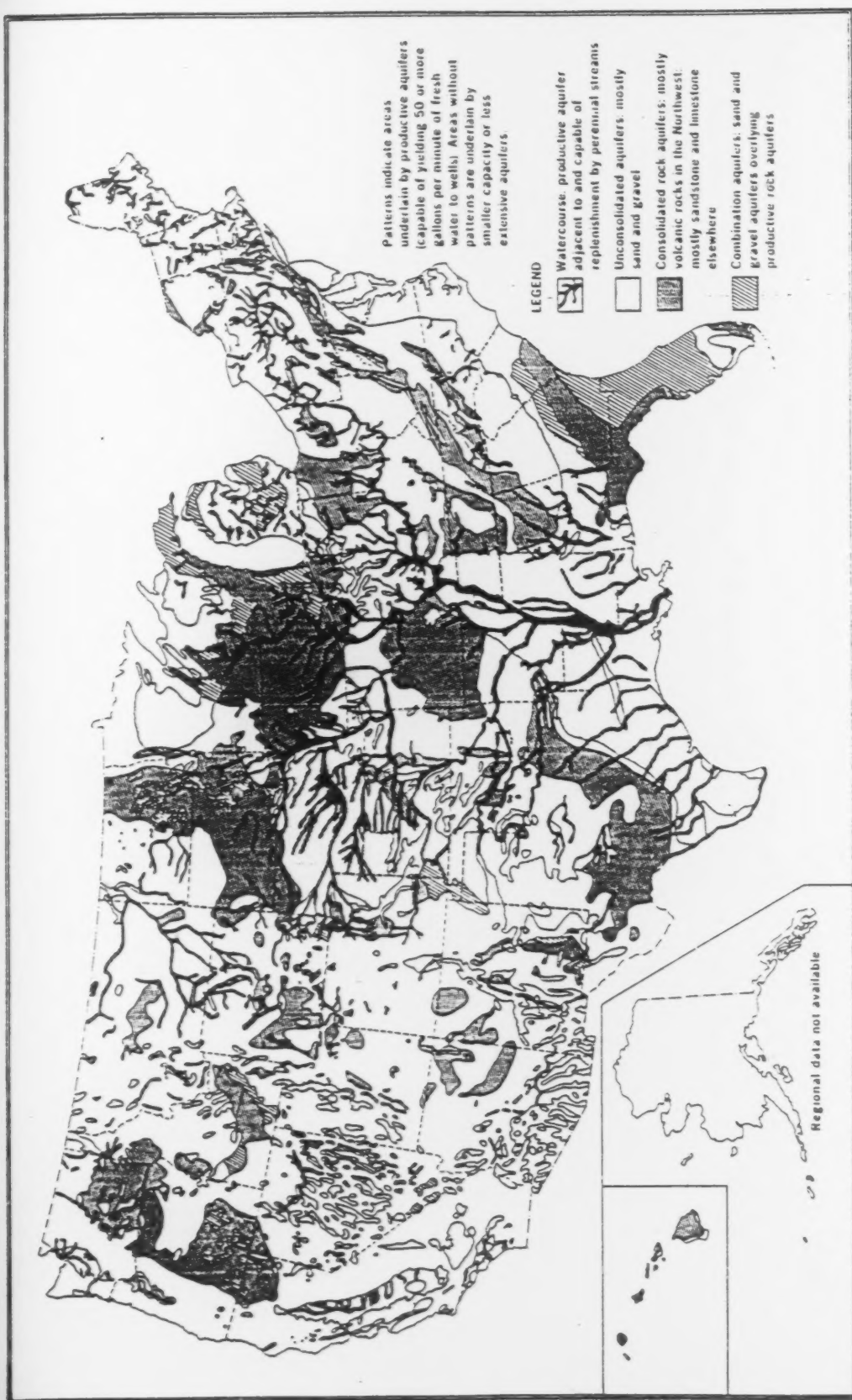


Figure 3. Major Aquifers in the United States (U.S. Water Resources Council, 1978).

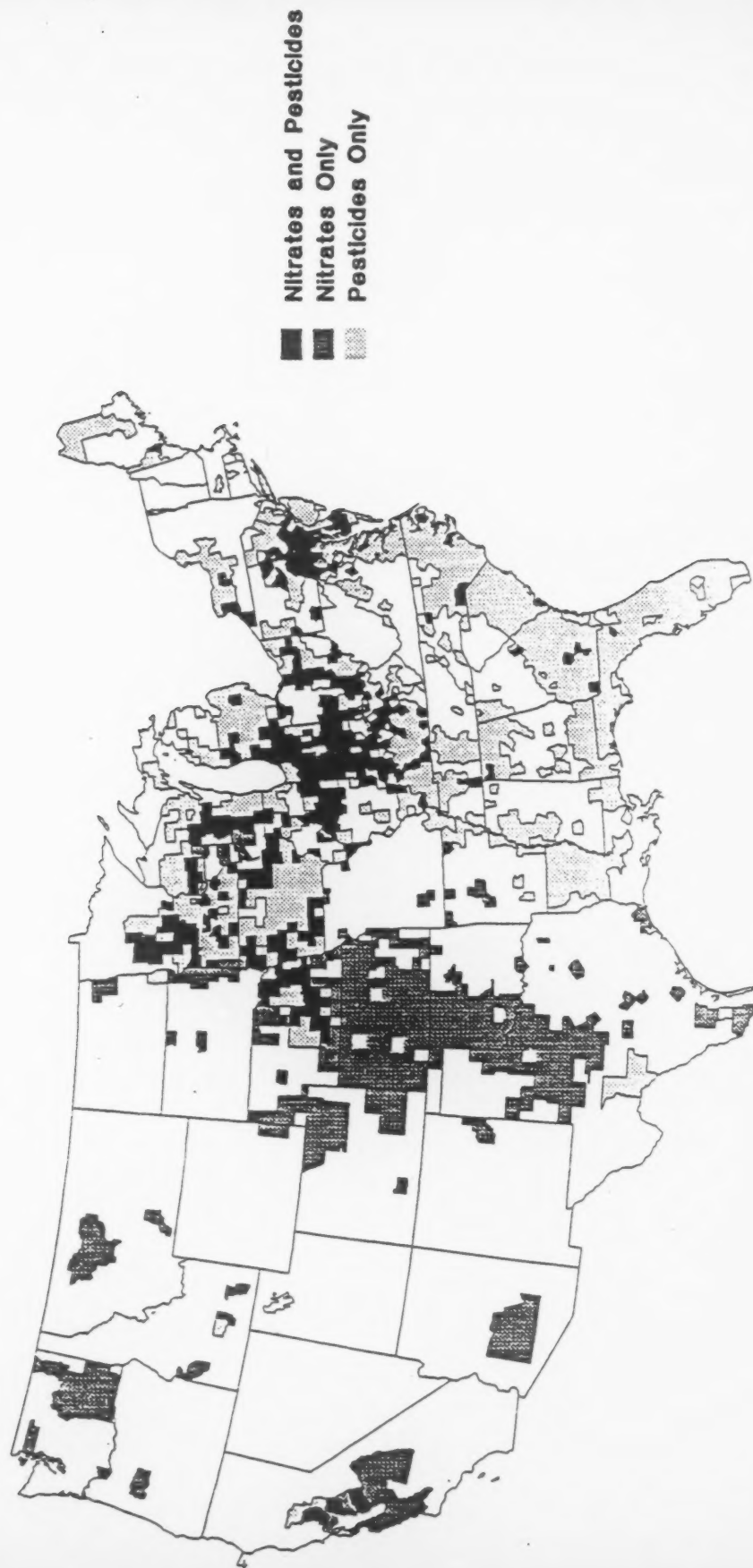


Figure 4. Areas of Potential Groundwater Contamination from Agricultural Chemicals (From Nielsen and Lee, 1987).



Figure 5. Distribution of Population Using Private Wells in Potentially Contaminated Areas (From Nielsen and Lee, 1987).

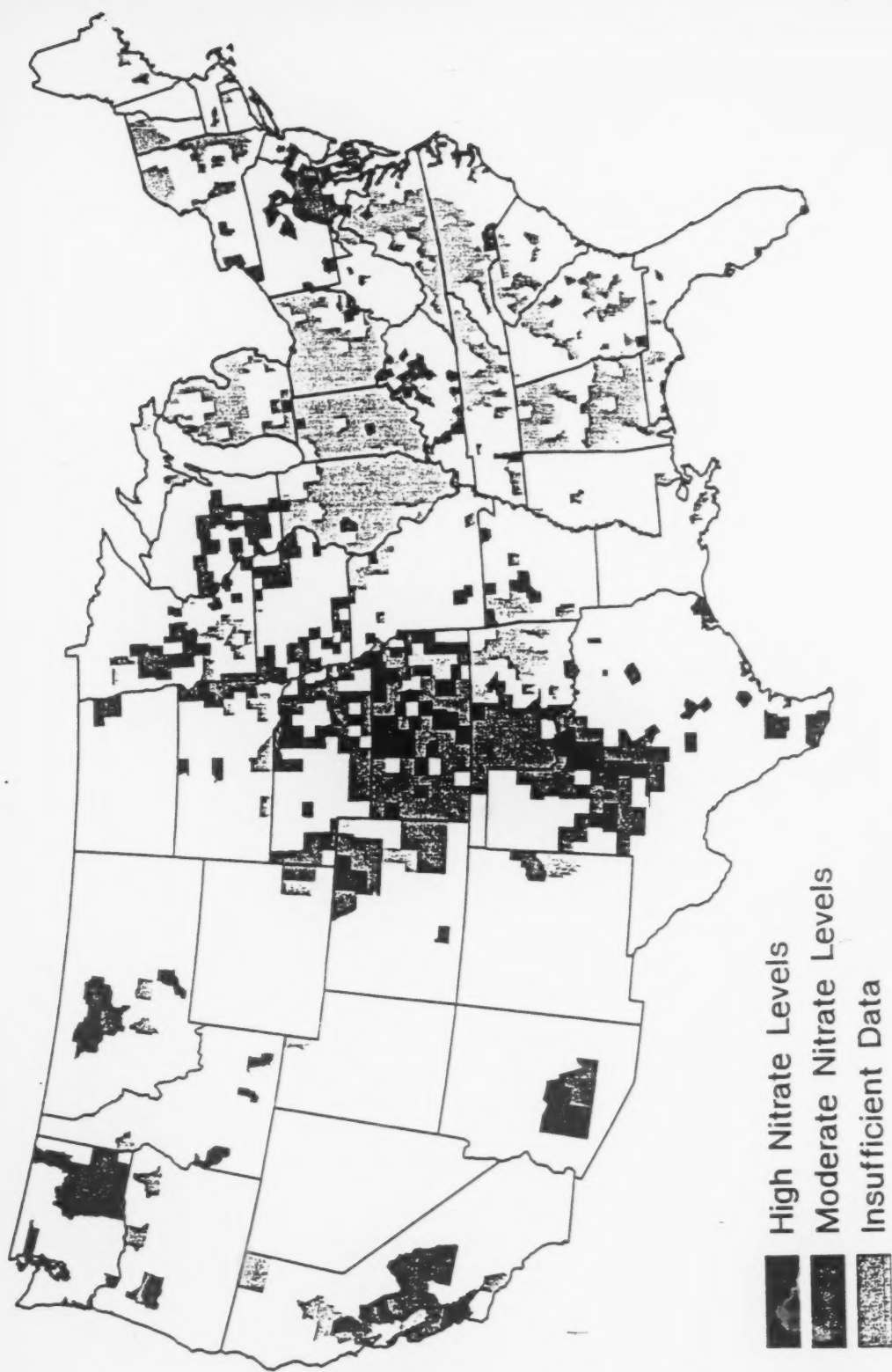


Figure 6. Nitrate-Nitrogen Distribution in Groundwater in Agricultural Areas
(From Nielsen and Lee, 1987).

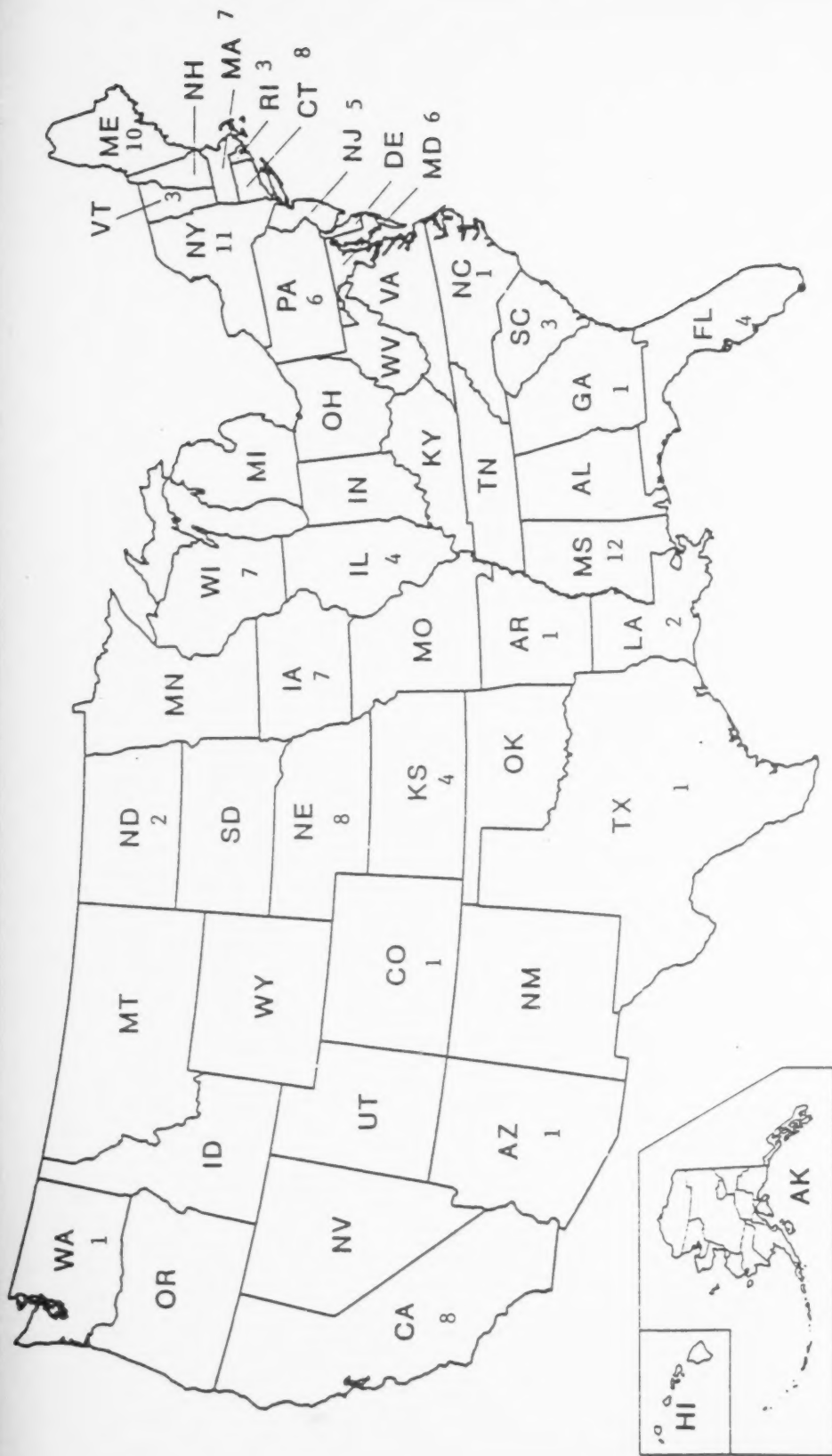


Figure 7. Numbers of Pesticides Found in Groundwater Caused by Agricultural Practices, 1988 (U.S. Environmental Protection Agency, 1988).

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***AGRICHEMICAL APPLICATION TECHNOLOGY: POTENTIAL
TO REDUCE GROUNDWATER CONTAMINATION***

by

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1 AGRICHEMICAL APPLICATION TECHNOLOGY:
2 POTENTIAL TO REDUCE GROUNDWATER
3 CONTAMINATION

4 Maurice R. Gebhardt, P.E.¹

5 I. Introduction.

6 A. Application methods and use patterns for sprays and granules.

7 Agricultural producers today are highly dependent on pesticides as an essential
8 component of most production systems. An estimated \$20 to \$40 billion may be invested in a new
9 product over a 7- to 10-year period before it is introduced for use (1). Often, the effectiveness of
10 these new products is only as good as the method of application. Yet, the amount of resources
11 invested in development of application equipment is so small that one can not make a realistic
12 comparison with the cost of pesticide product development. Almost 90% of the pesticides applied
13 today are applied with sprayers that have essentially the same components as sprayers in use 40
14 years ago. A majority of pesticides are applied as sprays with ground equipment as opposed to
15 application with aircraft or as granules with granule distribution equipment. Also, EPA approved
16 labels show the hydraulic sprayer to be the most prevalent approved method of applying pesticides
17 (1). Herbicides are the largest group of pesticides and are the pesticides that are most frequently
18 found in groundwater. In addition to the pesticides used on-farm for row-crop production, many
19 pesticides are applied with sprayers and granule applicators for horticultural and other specialty
20 crops, in states such as California, Texas and Florida. While the use of pesticides in horticultural

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1 and specialty crops is very important, the fact remains that herbicides used for weed control in row-
2 crops are the herbicides that are being found in groundwater (2). Furthermore, most herbicides
3 that are found in water supplies are the ones that are applied to soil either preemergence to the
4 weeds and crop or at planting time. Since the water contamination problem centers around the use
5 of herbicides, this paper will primarily deal with herbicide application technology. Most principles
6 of application for herbicides are applicable to other pesticides as well.

7 B. Research and development

8 The most important trend in equipment development is an effort to increase the
9 accuracy of application by improving existing sprayer components. Several new sprayer components
10 are now available that are designed to increase the efficiency of application. Many of these
11 components use modern electronics to control the sprayer application rate and to measure the
12 amount of spray applied per field or unit area. Several years ago there was considerable interest
13 in using rotary atomizers as a replacement for the hydraulic nozzle on sprayers. These rotary
14 atomizers allowed pesticides to be applied in much lower volumes of diluent than was commonly
15 used with hydraulic nozzles, with spray application rates of 5 gal/a as opposed to the 20 gal/a with
16 conventional spray nozzles. While rotary atomizers failed to replace hydraulic nozzles, the trend
17 to use lower sprayer application rates has continued. At about the time that rotary atomizers were
18 popular, several herbicides, were found to be more effective when applied postemergence at greater
19 concentrations in smaller volumes of diluent than what was being recommended. The trend toward
20 lower sprayer application rates continues with more pesticides being recommended for application
21 at 5 to 10 gal/a rather than 20 to 30 gal/a. This trend to use less diluent has required changes in
22 product labels and in some cases a change in formulation. It is very important to understand the
23 role of the diluent (water in most cases) in the application process. The diluent serves as a means

1 to meter and distribute formulated products to the target. Of the herbicides that are being found
2 in groundwater, most are applied preemergence on the soil. For soil application, water is used to
3 dilute the formulated product so that it can be distributed by the atomizers onto the soil surface.
4 While most research that pertains to the amount of diluent has been concerned with changes in
5 herbicide efficacy, there is no evidence to show a relationship between sprayer application rate and
6 the persistence of a pesticide in soil (3).

7 New formulations enabling more products to be easily applied as liquid sprays is
8 another trend. Some active ingredients are not easily diluted in water, requiring formulations so
9 they can be combined with water. Pesticides are formulated in several physical types that include
10 liquids (aqueous, oil, or emulsifiable concentrates), solids (dust, wettable powders, granules, or
11 encapsulated products) and gases (fumigants). The type of formulation depends on the chemical
12 nature of the pesticide, the target pest and other pesticidal properties. Formulated pesticide
13 products are made by combining seemingly inert ingredients with the active pesticide ingredient. Much
14 improvement has been made in formulations which allow the combining of materials that once
15 were very difficult to apply in water. Physical properties of the final spray material are very
16 important in the development of new sprayer technology. Techniques to measure the flow rate of
17 spray materials may be more easily accomplished now that improvements in formulations allow
18 the of materials to be easily measured. Accurate applications over a wide range of sprayer
19 application rates depends on a reliable, accurate means to measure flow rate. This trend of
20 improved formulations should encourage development of flow measuring devices that will eventually
21 lead to improvements in automatic controls for sprayers.

22 A recent trend toward the use of pesticides that are applied to plant foliage as
23 opposed to application on the soil along with a smaller range of recommended pesticide application

1 rates, now requires that the application process be more precise than it was a decade ago.
2 However, many of the older pesticides now being found in groundwater supplies did not have the
3 same requirement for precision of application. The range of recommended application rates for
4 many of these older soil applied materials is greater than the products that are applied to foliage
5 for postemergence weed control and for insecticides that are used to control insects on plants.
6 While an increase in precision may be good from the standpoint of reducing the potential for over-
7 application and thus decreasing the chances for pesticides to contaminate water within the soil,
8 requirements for precision may now be greater than the capabilities of present-day application
9 technology. If the present-day trend in precision continues, there is a critical need to invest a
10 significant amount of scientific effort into providing knowledge for improving agrichemical
11 application technology.

12 Another serious trend in pesticide usage is the application of several pesticides at
13 the same time. This simultaneous application of pesticides, often referred to as tank mixes, has
14 increased dramatically with the down-sizing of the agrichemical industry that has occurred in the
15 last few years. Many remaining companies have combined their own products with products from
16 a newly acquired company and developed special packaging techniques for marketing purposes.
17 These tank mixes have placed additional requirements on pesticide application technology,
18 especially for new injection type sprayers when up to three different pesticides may have to be
19 injected simultaneously during application.

20 Another change in application equipment occurred about five years ago when there
21 was much interest in applying pesticides at low- and ultra-low sprayer application rates. This trend
22 to apply less water with pesticides has created interest in the use of light-weight vehicles and other
23 smaller type applicators. Most of this development is being done by farmers and custom sprayer

1 operators and not by major machinery manufacturers. However, as the vehicles have become
2 lighter in weight, many of these light-weight sprayers are operated at speeds up to 10 mi/h, thus
3 enabling the application of considerable material in a short time. This trend to use lighter and
4 higher speed vehicles for spray application is going to continue because there are definite benefits
5 to using light-weight vehicles. These light-weight, high-speed applicators place additional
6 requirements on application technology. Additional research is required to provide the knowledge
7 needed for the development of these new technologies.

8 The major developers of pesticide application technology are limited to a very few
9 small companies that specialize for different types of markets. For example, one manufacturer may
10 specialize in farm sprayers designed for the small-farm market, while another manufacturer may
11 design their equipment for the custom applicator. However, most of this equipment uses the same
12 types of atomizers, valves, pumps and controls. Chemical application equipment is not considered
13 to be an important profit segment of the market by most large machinery manufacturers, but
14 essential to complement other product lines. In the U. S., there are only two major manufacturers
15 of nozzles, valves, screens and other hydraulic components for sprayers. Pumps are furnished by
16 several manufacturers, some that specialize only in pumps for pesticide application equipment.
17 Electric remote control valves and automatic sprayer controls and monitors are another separate
18 item used on pesticide application equipment. These electric components are usually furnished by
19 still another manufacturer. Many of these same independent manufacturers not only sell their
20 products to the manufacturer, but also sell direct to distributors for after-market sales as accessory
21 items for application equipment.

22 C. Chemical formulations and equipment development.

1 One of the greatest challenges for the pesticide application equipment developer
2 is the always changing product packages and formulations. While the chemistry of a pesticide
3 product may not change and will be on the market for many years, the formulation often changes.
4 Several of the larger chemical companies have just recently employed engineers or equipment
5 specialists who work with formulation specialists to coordinate formulation development with
6 application technology. At best, this recent effort is a token of the effort needed to properly
7 address problems in application. There is also a need to incorporate the development of
8 formulations with the assessment of biological activity and the fate of pesticides in the environment.

9 Many of the new pesticides are developed with design parameters that include, in
10 addition to their inherent biological activity, the ability to apply the material easily and with a fate
11 in soil and water that is acceptable. However, some of the older pesticides were not developed that
12 systemically, with a great deal of effort given to how the material would be applied and if the
13 pesticide would have an acceptable half-life in soil and water. Many of these materials were being
14 developed 20 years ago when the environmental concerns were very different than they are today.
15 For formulations that form suspensions, most sprayers are now better equipped with devices to
16 easily agitate the spray mixture to ensure that the formulated pesticide stays in suspension than they
17 were previously. Much improvement has also been made in the overall accuracy of application
18 equipment. Equipment is now designed to apply pesticides to within plus or minus 5% of the
19 recommended rate, a great improvement over the equipment used 40 years ago. Much of the
20 improvement has been made in the quality of components used on sprayers. Nozzles are more
21 accurately manufactured and sprayers now have other improved hydraulic components such as
22 pumps, valves, strainers, and controls than they did four decades ago. As mentioned before,
23 sprayers use the same components as they did 40 years ago. However, the quality of those

1 components has greatly improved, especially in the last 10 years.

2 D. Application efficiency.

3 There is much discussion among scientists and engineers about how to assess the
4 efficiency of a pesticide, let alone how one can assess the application processes. From a simplistic
5 standpoint, one can assume that the application processes must take the formulated product from
6 the original container and place a precise amount on the target. At first, this seems rather straight
7 forward, provided that the target and its environmental conditions are known and constant
8 throughout the field. Targets for herbicides include the soil (prevent germination or kill seedling),
9 roots, rhizomes and other underground tissue, and in the case of foliar application, stems, apical
10 shoots, and leaves (4). In the case of herbicides applied to the soil prior to planting or at planting
11 time, the target is the top 1.5 inches of soil. The purpose of this application is to provide enough
12 herbicide so that the concentration of active ingredient in the water, water vapor and on soil
13 particles within the soil is great enough to prevent germination or kill certain weed seeds that
14 germinate within this zone of concentration. The weight of herbicide is very small in comparison
15 to the weight of soil contained in this zone of application (5). There are many variables within and
16 on the soil surface that influence the efficacy of a pesticide. The amount of moisture, the soil
17 temperature, and other physical features of the soil affect the biological activity of a pesticide. In
18 addition to these physical features of the soil that can affect pesticide performance, there are a
19 multitude of biological processes within the soil that can influence pesticide activity. Often, it is
20 very difficult to predict what affect these variables will have on a particular application of a
21 pesticide to the soil. One could contend that the amount actually required to prevent weeds from
22 germinating and growing is much less than that applied, thus leading one to think that too much
23 pesticide is being used. The problem with this contention is that such an application requires that

1 all the active ingredient be placed within or on the target species. Often the nature and occurrence
2 of the target specie varies considerable within the soil as well as within the field area. For example,
3 soil organic matter is known to vary considerable within many fields throughout the Corn Belt (6,7).
4 The amount of herbicide required to control weeds when applied preemergence depends greatly
5 on the amount of organic matter within the soil. Sensors are needed to measure the organic matter
6 on-the-go so that herbicide rates could be varied according to the level of organic matter in the soil.
7 Organic matter and other sensors such as sensors for detecting foliage would increase the efficiency
8 of the application process without affecting the efficacy of the pesticide.

9 While some effort has been put forth to improve application technology from a
10 pesticide efficacy standpoint, little has been done in an attempt to monitor and control the
11 application processes such that less active ingredient is allowed to contaminate the environment.
12 The approach has been mainly on providing the minimum amount, at the right time, and at the
13 right place, providing that the product satisfactorily controls pests. There is good justification for
14 this approach because of the strong emphasis that has always been made to apply the minimum
15 amount needed to satisfactorily control pests. The EPA and state regulatory agencies have always
16 been concerned about the effect of pesticides on the environment when applied at a recommended
17 use-rate. A great deal of effort goes into setting the recommended use-rate for a pesticide. The
18 manufacturer is faced with a difficult decision that often is a compromise between the risk of
19 product failure if the rate is set too small, and a risk of not receiving approval by the regulatory
20 agencies, if set too large. Also, often pesticides are used to selectively control some species while
21 not controlling others, requiring that the rate be small enough to not affect beneficial plants or
22 other organisms, yet large enough to control the pest. The recommended use-rate is set after
23 exhaustive field trials have been made under as much variation in climatic conditions as possible.
24 There are times that even after this exhaustive evaluation, chemical companies have had to adjust

1 the use-rate after the first year, while under restrictive sales conditions. Simply put, if it doesn't
2 work, it won't sell and if it doesn't sell the company loses their investment. Since the companies
3 are in business to sell a product, the product must control pests. It may be that the level of control
4 that many were used to with some of the older products, may have to be compromised for less
5 control, if a method is not found to safely use these older products.

6 From an application standpoint, there is little that can be done to control the fate
7 of a pesticide after it is on-target. Losses of pesticide during the application and prior to deposition
8 may be more important than the fate of the active ingredient after deposition. Losses, especially
9 during mixing and filling of tanks and hoppers offers a much greater potential for contamination
10 of surface and ground waters than losses during application. There is a need to improve the
11 technology and procedures for storage, handling, and mixing of pesticides and other agrichemicals.

12 While some material is lost to the air while the spray moves from the atomizer to the target, this
13 loss is thought to be rather small from a water contamination standpoint. However, from an air
14 pollution standpoint, losses from drift and evaporation during application can be of great concern.

15 II. Technical Assessment

16 A. Application methods and associated equipment

17 The first documented assessment of application technology was from a Nebraska
18 study (8) summarized in an article titled, "The Billion Dollar Blunder," from *Successful Farming*,
19 April 1980 (9). From the early 1980's, there have been numerous meetings and conferences with
20 a focus on agrichemical application technology and it's role in the fate of chemicals in the

1 environment. The first serious assessment was a result of the conference, "Changing agricultural
2 production systems and the fate of agricultural chemicals," organized by the Agricultural Research
3 Institute in 1984 (10). Among one of four recommendations made by the conference participants
4 was, "a national conference on equipment and practices designed to improve agricultural chemical
5 application technology." Such a conference was held in March of the following year (11). In
6 summarizing the conference proceedings, Dr. Franklin Hall, chairman of the conference said,
7 "Increasing costs, a greater number of highly efficacious chemicals, and a growing concern for
8 environmental pollution make it essential that pesticides be applied more efficiently." It is difficult
9 to understand that in the U. S. it was not until 1985 that the first national conference was held on
10 such an important subject when in Europe, such conferences are rather common. It is not difficult
11 to see why agricultural chemical application technology and the farm equipment industry here in
12 the U. S. has fallen far behind similar technology in other countries.

13 The improvement of herbicide application technology has lagged even further behind
14 the interest in improvement of equipment to apply insecticides and fungicides which is hard to
15 believe when the largest amount of pesticide usage is herbicides. The increased use of herbicides
16 that are applied postemergence and a requirement for greater precision in application has caused
17 the herbicide industry to become more concerned about the efficiency of the application processes.
18 Many problems related to the application of pesticides were summarized as follows (11):

- 19 1. Insufficient interdisciplinary research.
- 20 2. Low priority for funding by private and public research bodies.
- 21 3. Chemical technology advancing more rapidly than application technology.
- 22 4. Insufficient adoption of technology and engineering concepts from other sciences
23 and industry.

1 A follow-up to the application technology conference was held at Reston, VA on June 13-15, 1988
2 (12). This conference, also organized by the Agricultural Research Institute, was entitled
3 "Improving on-target placement of pesticides." Topics at this conference included improved
4 operator training, pesticide handling, packaging, and transfer, and aerial application. While the
5 conference in 1985 focused on hardware, in 1988 the conference focus was shifted to operator
6 training and technology for improved operation of pesticide application equipment in addition to
7 an overwhelming need to improve equipment and procedures for the handling, packaging, and
8 transfer of pesticides. Except for aerial application equipment, the 1988 conference gave more
9 attention to storage, mixing, transfer, and handling facilities. In the case of aerial application, there
10 was still a need to better understand the role of droplet size distribution on drift and losses during
11 application and to develop operational solutions to drift problems.

12 While the reports from all these conferences have strongly recommended that
13 specific actions be taken by industry, states and federal agencies, very few of the recommendations
14 have been followed. At the present time there is widespread interest in improving the quality of
15 our groundwater supplies. The focus of this interest seems to be on the active ingredients of the
16 products and not necessarily on formulations, application technology, and operational procedures.

17 B. Extent of use and major users

18 Up-to-date information and data on agrichemical usage is very scarce. As a result
19 of special appropriations from the U.S. Congress in 1964, the Economic Research Service of the
20 U.S. Department of Agriculture provided a great deal of information on pesticide and fertilizer
21 usage from the mid-sixties up until the early 1970's. The purpose of this information was to provide
22 a basis for determining costs and benefits for pesticides and to determine trends in pesticide usage

1 (13). However, published information for the early eighties is limited and published pesticide use
2 data for the mid-eighties is almost non-existent. For the Corn Belt, the percentage of acres treated
3 with herbicides increased from 81% in 1972 to 98% in 1980 (14). There is little reason to believe
4 that there has been much change in the percentage of acres treated with herbicides in the Corn Belt
5 (15). As mentioned in the introduction, A majority of pesticides are applied as sprays with ground
6 equipment as opposed to application with aircraft or as granules with granule distribution
7 equipment. Corn and soybeans crops continue to be the crops with the most herbicide usage,
8 accounting for almost 70% of the amount spent on herbicides used in 1980 (16). While the
9 percentages are probably correct the amount of pesticides has changed because of such factors as
10 the Conservation Reserve Program and some changes in types of pesticides used that has been
11 caused by the introduction of new products. There is an urgent need for an accurate assessment
12 of agrichemical use and use-patterns that reflect current farming practices.

13 C. Crop specificity

14 The type of application equipment is difference depending on the crop that is
15 treated. Aircraft usage is generally greater in the South, Southeast and the West. Cotton
16 production accounts for a greater use of aircraft in the Southeast and brush and weed control on
17 range lands along with greater applications of insecticides for cotton production requires greater
18 use of aircraft in the deep South and in Texas. For custom application, the amount of acres treated
19 with aircraft is estimated to be about the same as that treated with ground equipment. In general,
20 the acres sprayed with a pesticide increases as you move south, with a greater number of trips
21 across the field in the cotton growing regions of the U.S. In the Corn Belt, almost all the pesticides
22 are used on corn and soybeans. The type of application equipment is the same for both crops with
23 almost all the acreage treated using ground equipment. Therefore, for those herbicides that are

1 being found in Mid-Western groundwater, most are applied with field sprayers by farmers and
2 custom applicators. The custom applicators use larger sprayers specifically designed for treating
3 greater acreage between refilling.

4 D. Chemical formulations appropriate for the problem

5 A pure pesticidal product would essentially be ineffective if used in a pure form.
6 The formulation provides (a) dispersion of the product in the application media (usually water),
7 (b) product integrity and stability during storage (shelf live) and (c) the ability of the pure pesticide
8 to move through lipid barriers to a biological site of activity. Most of these properties are
9 concerned with increasing the efficacy of pesticides that are applied to plant foliage. There has
10 been increased interest in pesticide formulation chemistry with an emphasis on increasing the ability
11 of the product to move through the wax layers on leaf surfaces. These properties not only increase
12 the efficacy of a pesticide, but also increase the retention of the spray on plant surfaces thus
13 reducing losses of pesticides either to the air or onto the soil surface, thus reducing the potential
14 for pesticides to move into the soil (17).

15 The role of adjuvants on the movement of pesticides in soil has been investigated,
16 but not as much effort has been given to these relationships as that given to the role of adjuvants
17 on retention and sorption of pesticides on plant surfaces. Surfactants have been used to enhance
18 infiltration of water into soil where surface sealing might occur in forests where fires have made
19 the soils water repellent (18). Except for hydrophobic soils, adjuvants have been found to have little
20 effect on the physical properties of soils. There is some evidence that surfactants in fertilizers may
21 have an effect on the evaporation of water from the soil surface (19). Some pesticides abilities to
22 adsorb or absorb on soil particles can be affected by adjuvants. In some cases, the mobility of

1 pesticides within the soil have been enhanced by the use of a surfactant.

2 E. Efficacy

3 Much effort has been devoted in an attempt to increase the efficacy of pesticides
4 by methods of application. While earlier research was concerned with improving the reliability of
5 application equipment, recent efforts have more to do with increasing the deposition, retention, and
6 sorption of pesticides on plant foliage. While it is known that the efficiency of many application
7 techniques is relatively low, there has been little progress made to improve the processes. The lack
8 of improvement can be attributed to the inherent variation that occurs in biological systems. Most
9 of the positive results from improved application technology such as droplet size studies have only
10 been obtained at marginal pesticide rates of application. It is difficult to show an improvement
11 from new application technology at recommended pesticide application rates. Recommended
12 pesticide application rates have a built-in margin of error that accounts for poor application. The
13 chemical properties of the active ingredient, and more importantly, the formulation, has much more
14 to do with efficacy than physical properties of spray materials. Therefore, it is very difficult to show
15 an increase in efficacy due to improvements in application technology. That is not to say that there
16 are no possibilities for improving the efficacy with application technology. At the present time,
17 given the inherent variability in biological systems and the overwhelming effect of formulation
18 chemistry on application efficiency, improvements in the physical nature of sprays has little effect
19 on the control of pests. Improvements in application will be necessary as we better understand the
20 processes involved in the control of pests and how the active ingredients are affected by adjuvants
21 and formulation chemistry. The greatest opportunity for improvement is accommodating the
22 variability in the amount of pesticide to apply within a field. Technology within the military/indust-
23 rial complex is available for transfer to agriculture, particularly for the control of the application

1 process. Automatic guidance of sprayers and other application equipment would improve the
2 efficacy of many products by eliminating skips and double application. Improved flow rate
3 measurements would make it possible to improve the accuracy of the application of many pesticides.
4 These improvements, while they themselves may be small, when aggregated, they can have a
5 significant effect on the efficacy of a pesticide.

6 F. Opportunities and/or constraints to adoption

7 It is often difficult to determine what factors are most influential in the adaption
8 of agricultural technology. Much depends on the financial climate and weather conditions over
9 the past couple of years. At the present time, farmers in the Mid-West are recovering from the
10 severe drought of 1988 and are very reluctant to make significant investments in new technology.
11 On the other hand, after the 1989 crop is harvested, they may be much more interested in new
12 developments. When considering new technology, most farmers, first want to see if the new
13 technology will increase their profits, and secondly will it give them more time for other activities.
14 While farmers are always concerned with staying in business, they are also very concerned about
15 their use of agrichemicals, especially as related to the quality of rural water supplies. They want
16 to know if there are any changes that can be made in their use of agrichemicals that can ensure that
17 their water supplies will not be contaminated. Most are very hopeful that there are alternatives to
18 some of the present-day practices and are willing to consider these alternatives. No one knows for
19 sure the amount of extra expense they are willing to allow for these alternatives. Many farmers are
20 influenced by their peers within the local community. They are very aware of what their neighbors
21 do, just like in any business. A good business person always knows what the competition is doing.
22 While the competitive spirit is not as strong in rural america as other businesses in urban areas,
23 farmers want to be using the latest technology. However, they often want their neighbors to try out

1 the new practices before they adapt the new technology. Several years ago, many farmers thought
2 that the rotary atomizer was going to allow them to use less pesticide. Many farmers purchased
3 these atomizers with cost savings in mind. They were disappointed to later find that rate
4 adjustments were also possible when herbicides were applied with conventional application
5 equipment. Experiences like the case of the rotary atomizer make it difficult for small sprayer
6 manufacturer. The creditability of some small sprayer manufacturers is not nearly as great as that
7 of the major machinery manufacturers. It is unfortunate that the larger machinery manufacturers
8 did not take a greater part earlier in the development of pesticide application equipment. The
9 amount of money spent on chemicals often exceeds that spent on seed. Yet, the complexity and
10 cost of many planters is greater than many farm sprayers. However, many large farm operators and
11 custom applicators now are beginning to use the latest equipment for monitoring the application
12 of pesticides and other agrichemicals. Some have realized that precision of application can be a
13 real cost-saver in their operation while others are not very concerned about pesticide application.

14 G. Potential for improving current methods and equipment

15 The greatest opportunity for decreasing the potential of contaminating water supplies
16 with improved application technology can be realized by increasing the accuracy and placement of
17 pesticides. Most studies of farm sprayer accuracy show that from a whole-field standpoint, farmers
18 are applying less than they thought they were applying (8). However, recently, farmers have
19 become concerned that they are applying their products evenly within the field. Whether uneven
20 application within the field contributes to the water quality problem has yet to be determined. It
21 will be very difficult to measure the influence of uneven application on the movement of pesticides
22 into the soil when considering the many other factors that influence the fate of pesticides in soil
23 and water. It appears that greater improvements can be made in the storage, transfer, mixing and

1 handling of agrichemicals as sprayers and spreaders are being filled and re-filled both in the field
2 and at the farmstead. The next improvement that should be considered, is an overall improvement
3 in the accuracy of the spraying operation. This includes such rather routine matters such as
4 calibration and correct mixing calculations for applications of both pesticides and fertilizers.
5 Improved equipment is available to aid in the calibration and monitoring of the application process.
6 However, many of these devices also need to be checked or calibrated. There is a concern that
7 farmers will become too dependent on this technology and that accuracy will decrease with this
8 dependency. Proper education in the use of this new technology is very critical for continued
9 accurate applications. These educational programs should stress the manual calibration of the spray
10 equipment and the replacement of sprayer components when wear is indicated by the calibration
11 tests. Sprayers can easily be retro-fitted with monitoring and control devices that will improve the
12 accuracy of the application process. Nozzle manufacturers are very concerned about the quality of
13 their nozzles and other sprayer components. These manufacturers have initiated comprehensive
14 educational programs for distributors and dealers. Some pesticides require that they be mixed or
15 incorporated into the soil as they are applied. New incorporation equipment and more educational
16 programs could achieve improvements in the incorporation of some products. The greatest problem
17 with incorporation is caused by mixing the product too deep within the soil profile where the
18 product is located away from the target pest and subject to further movement into the soil from
19 heavy rains or irrigation. It is very difficult to precisely place pesticides within the soil when many
20 variable factors influence the movement and fate of the pesticide within the soil profile.

21 There are some opportunities for improving the application process with existing
22 equipment by improving formulations. Products are available for improving the droplet size
23 distribution within sprays to decrease drift and loss of pesticides. While these losses can be
24 significant as an air pollutant, drift of products away from the intended area of application can

1 hardly account for any significant increase in ground water contamination except for surface water
2 sources. Drift of sprays into lakes and streams could account for contamination of water sources.
3 Therefore, there is a need to demonstrate that these drift reducing additives significantly reduce
4 the movement of pesticides from the intended spray area. While these additives often alter the
5 distribution of droplet sizes within the spray spectrum, they may not eliminate the small satellite
6 drop that often forms when larger droplets develop within the spray cloud.

7 H. New and emerging application technologies

8 Electrostatic spray techniques have been under development for many years. While
9 this technology is very successful for the commercial painting industry, this technology has yet to
10 demonstrate a significant, consistent improvement for applying pesticides in agriculture. The
11 greatest potential for this technology is for the application of insecticides on plant foliage for insect
12 control where coverage is very important. Very little improvement has been shown for the
13 application of products to the soil with electrostatic sprayers. If farmers were required to rely on
14 the use of herbicides that are applied postemergence, then electrostatic spraying techniques have
15 the potential for eliminating the application of these products to the soil. This would be very
16 important if these herbicides that are applied postemergence were not readily degraded within the
17 soil. However, at the present time, most of the herbicides that are used postemergence, have not
18 been found in ground water and are products that readily break down on and in the soil.
19 Therefore, the use of electrostatics for decreasing the potential of pesticides to contaminate water
20 is limited in the short-range, but could be important in the future.

21 Improved maintenance and calibration technology is the most significant short-range
22 improvement that can be made to agrichemical application equipment. Much of this technology

1 does not require a large amount of research, but will require time for development. There is a lot
2 of technology available for transfer to agricultural from the military/industrial manufacturing
3 complex. Much of this technology will need to be scaled-down and simplified for use on the farm.
4 While this effort many seem rather straight forward, it is very difficult to accomplish given the
5 present status of the farm equipment industry. None of these equipment manufacturers are in a
6 position to spend large amounts on the development of this technology without passing these
7 expenditures along to the user by increasing the cost of the equipment. The investment in farm
8 equipment accounts for the largest single production cost in row-crop production and any significant
9 increase in machinery cost will further decrease the American farmer's ability to remain competitive
10 in today's world market. The agrichemical application machinery industry is not concentrated in
11 a few companies like other industrial products. None of these companies have any research
12 capability for chemical application technology and few have the resources to develop equipment
13 from other technology. Several companies now offer kits for aiding in calibration. The greatest
14 problem is getting the farmer to realize the importance of calibration and not that of obtaining the
15 equipment for calibration. Improvements in the plumbing on sprayers could be made to facilitate
16 removal of unused spray mixtures and for cleaning the spray tanks and other components.

17 Direct chemical injection systems for sprayers provide a means to eliminate any
18 residual pesticide mixture upon completion of application. Eliminating this residual spray can
19 have a significant impact on the contamination of water supplies. Often, the on-farm and
20 commercial mixing sites are near wells and other sources of water. Many of these sites lack
21 facilities for containment when spills are likely to occur while disposing of the unused spray
22 material. Some farms that do have lagoons, catchment basins, or other surface storage
23 containments may not have them designed to prevent movement of the spent material into water
24 sources. Therefore, the direct injection of pesticides on-the-go is a technology that should be

1 thoroughly evaluated for further adaption by sprayer manufacturers. The injection sprayer mixes
2 the formulated pesticides in the plumbing of the sprayer on-the-go as the application is being made
3 in the field. No pesticide product is pre-mixed or handled with this type of sprayer. The large
4 tank on the sprayer is used to store the diluent, usually water. With this type of sprayer, only the
5 pesticide actually applied is mixed into the spraying system, thereby eliminating any residual
6 material to clean out of the tank when spraying is completed. This technology has been under
7 development for several years and is now commercially available² (20,21).

8 About 10 years ago the state of California enacted legislation requiring the use of
9 closed systems for the mixing and transfer of certain agrichemicals from storage facilities into field
10 sprayers, thus vertically eliminating the mixing of pesticides with the diluent while in the field.
11 These systems have become known as the California closed systems. While these systems were
12 designed to reduce worker exposure to pesticides, the closed systems can provide additional hazards
13 with respect to contamination of water sources. The closed systems offer an opportunity for rather
14 large amounts of formulated product to be concentrated in bulk at or near water sources such as
15 lakes, ponds, wells, and canals. These rather large bulk containers are often brought to the mixing
16 site where the closed system is located. Without provisions for containment, this concentration of
17 pesticide poses the potential for contamination if a leak should occur either in the bulk tank or in
18 any connecting plumbing. These closed systems are often very complex and expensive with little
19 evidence that they actually reduce worker exposure or reduce the potential for water contamination.

20 Losses of agrichemicals during the spraying operation can be reduced by shrouds
21 or shields that are used to reduce the effects of wind and other environmental conditions might
22 have on drift, evaporation, and other losses. While these losses may have a significant effect on

23 ²Midwest Technologies, Inc. 625 E. Kimble St., Springfield, IL 62703

1 air quality, it is not believed that reduction of these losses will have an effect on water quality
2 other than for special situations when spraying near surface water sources.

3 Wicks, rollers and other wiping devices have been used for topical application of
4 herbicides to plants for about 10 years. These devices offer the best method available to effectively
5 eliminate the application of herbicides onto the soil. However, these devices require that the weeds
6 have grown enough to provide sufficient foliage and stems for the topical application. While at first
7 this procedure seems rather straight forward, keep in mind that all weeds do not germinate and
8 grow at the same rate. Addition trips across the field may be necessary in order to obtain adequate
9 control. Nevertheless, this technology needs further development if it becomes necessary to rely
10 on the use of herbicides that are only applied postemergence. If the banning of soil applied
11 herbicides should occur, then topical and other techniques for effective application of herbicides
12 on foliage and other plant parts will become increasingly important.

13 Mechanical pest control methods were quite common prior to the development of
14 modern pesticides. Even today, farmers continue the cultivation of row-crops to control weeds even
15 if they have used herbicides for controlling early weed growth. Many specially crops require
16 cultivation several times during the growing season. However, corn acreage in the Mid-West
17 receives very little cultivation when compared to soybeans. The difference between corn and
18 soybeans results from the availability of a long-lasting residual type herbicide like atrazine for corn.
19 In general, herbicides applied prior to planting of soybeans are not as long-lasting as those used in
20 corn. Also, in the Mid-West, soybeans are normally planted later in the season than corn, thus
21 allowing more time for weeds to germinate prior to and after planting. Therefore, soybeans
22 normally require some type of postemergence weed control, either the application of a herbicide
23 or mechanical cultivation. Row-crop cultivation of soybeans depends on the time available which

1 often is related to the diversification of enterprises on the farm. Many farmers with livestock
2 operations will use herbicides for postemergence weed control because they need time for haying
3 which often occurs at about the time that mechanical cultivation should occur. Other than row-
4 crop cultivation, other mechanical pest control methods have not been found to be as effective as
5 chemical pesticides. Blowers and vacuums have been used for removing insects and fallen cotton
6 squares. However, none of these devices have been found to be as effective as current integrated
7 pest control methods.

8 I. Constraints and opportunities to development and/or adoption

9 The discovery of new knowledge for pesticide application technology has been made
10 in large-part by public research agencies. As mentioned before, none of the chemical application
11 companies have the ability to conduct fundamental research that relates to equipment development.
12 In the mid-1970's, the Food Machinery Corporation (FMC) was devoting some effort in the
13 developing an electrostatic sprayer as well as other improvements of application equipment.
14 However, in the early 1980's, FMC eliminated all their pesticide application equipment development
15 work. At the present time, the greatest effort in the commercial sector is with some of the new
16 companies that are manufacturing electronic devices for chemical application equipment. There
17 has been some adoption of knowledge that was discovered in the public research laboratories. For
18 example, the injection sprayer, now manufactured by several companies was developed from the
19 research conducted by people in federal and state research laboratories. Recent changes in the
20 patent laws (Technology Transfer Act) now encourage the joint development of technology for
21 improving chemical application. The effect of this new legislation is just now beginning to be seen
22 as more engineers and scientists in federal and state laboratories are starting joint proprietary
23 developments with industry.

Table 1. Agricultural engineering research for weed control equipment development (1).

Year	ARS	State	Total
	(SY)	(SY)	(SY)
1972	8.7	2.4	11.1
1974	4.3	2.0	6.2
1977	2.9	1.5	4.4
1979	2.8	0.7	3.5
1982	1.7	0.8	2.5

1 The research effort devoted to the development of chemical application has
2 continued to diminish as shown in Table 1. While these data are only for those engineers working
3 on equipment for applying herbicides for weed control, similar trends can also be found in equip-
4 ment development for insect and disease control as well as for machinery development in general.
5 It is very unlikely to find any changes in these trends since 1982. Pesticide application equipment
6 development started to grow in the early 1960's and reached a peak in the early 1970's. In 1963,
7 a special conference on pesticides was held in conjunction with the American Society of Agricultural
8 Engineers (ASAE) 1963 Winter Meeting (22). One of the purposes of this symposium was to
9 recognize the establishment of new research thrusts on pesticide application equipment in the
10 Agricultural Research Service and in the State Universities. The meeting was sponsored by the
11 Farm Equipment Institute (FEI now the FIEI, Farm and Industrial Equipment Institute) and
12 ASAE. Then in the middle 1960's a Council on Pesticide Application was formed to coordinate
13 research and development by the major manufacturers of chemical application equipment. Several
14 seminars and meetings were held when major issues required coordination of efforts (23). All of
15 these meetings and conferences recognized that basic and applied research was required to keep
16 up with the rapid growth of the pesticide industry. Since the early 1970's there has been a steady

1 decrease in industry efforts as well as within public research agencies. The FIEI no longer has a
2 Spray and Duster Council and the Council on Pesticide Application no longer exists. Resources
3 in the public agencies have essentially been used to keep up with inflation by reducing the number
4 of people involved in this type of research. The congress has provided some additional funds for
5 agrichemical research in the Agricultural Research Service (ARS) in the past several years. These
6 funds have been used to increase research at Stoneville, MS and Wooster, OH, where ARS already
7 has a considerable investment in application equipment research. Plans are being made for
8 increasing the research for application research if new funds become available for a water quality
9 initiative in the 1990 budget. Most of these efforts will be short-range (3-4 yrs) and are essential
10 to develop improvements using existing knowledge or the transfer of knowledge from other
11 industries. It is doubtful that resources will be available to do the long-term research needed to
12 provide the knowledge-base required to make a significant change in agrichemical application
13 technology.

14 The major efforts in agrichemical application research is within ARS, at some
15 agricultural research stations, and in some companies that supply controls, atomizers, and accessory
16 items for sprayers. ARS has the largest investment in this effort which is concentrated at several
17 locations in the U.S. Scientists and engineers at these locations are very active within their own
18 disciplines and are known within the agrichemical application equipment industry. There is good
19 communication between the industry and the people who are doing equipment development
20 research. However, the amount of effort in equipment research within the Corn Belt is rather
21 limited. Except for Wooster, Ohio, most of the effort is either in the Southeast or in Texas. States
22 near the major manufacturers of either nozzles or farm machinery has limited work in pesticide
23 application technology.

1 The development of chemical application equipment by European companies is
2 very similar to the development of other farm machinery by companies located outside the U.S.
3 Over the past five years, no tractor under 60 HP has been manufactured in the U.S. The U.S. is
4 becoming dependent on Europe for tractors and many other farm machines. The greatest amount
5 of effort in agrichemical application equipment appears to be in the U.K. and in some eastern
6 European companies. The development of improved granule distribution equipment came from
7 France and we are beginning to see more chemical application equipment at U.S. machinery shows
8 that is from other European companies . However, most of the sprayers now being used in the
9 Corn Belt are still made here in the U.S.

10 While the agrichemical application equipment industry is large when you consider
11 the number of applicators in use, this industry is scattered among many small manufacturers and
12 equipment suppliers. The industry is not concentrated so that there is enough profit incentive for
13 any major manufacturer to invest considerable resources in new product development. After the
14 introduction of 2,4-D in the early 1940's, there were literally thousands of very small (back-yard
15 type) companies making sprayers. The few major manufacturers in existence at that time simply
16 did not respond fast enough for the rapid demand for field-type row-crop sprayers. Many of these
17 companies were making high-pressure orchard sprayers for the application of insecticides in
18 specialty crops. The other major farm machinery manufacturers were so busy meeting the demand
19 for tractors, combines, planters, and tillage equipment that they were glad that these small
20 manufacturers were there to meet the demand for sprayers. In fact, some of the major
21 manufacturers sold chemical application equipment that was furnished by a third-party manufactur-
22 er. These companies wanted to have the application equipment on hand to complement their
23 product lines.

1 There apparently are no great disincentives for private company development of
2 new agrichemical application equipment other than the present rather narrow margin of profit for
3 the farm machinery industry. Most of the improvements that will have to be made to minimize the
4 contamination of water will not necessarily increase the efficiency of application and reduce
5 production costs. Therefore, the added cost of these improvements will ultimately have to be
6 passed on to the farmer in the form of added machinery costs. The farm machinery industry is
7 willing to respond with improvements if they know that these improvements will have a market.
8 The market will depend on whether the farmer is willing to pay more for equipment that will
9 decrease the chances that agrichemicals will decrease water quality. The incentives and
10 disincentives for the machinery industry are very similar to that of the chemical industry. For some
11 pests, pesticides are available to substitute for the ones being found in groundwater. However,
12 these newer pesticides cost more and in some case are not as effective as the ones being found in
13 groundwater. It is difficult to determine if farmers are concerned enough to pay the extra price to
14 ensure that their practices are not contributing to the water quality problem. The same situation
15 is true for the machinery industry. Will the farmer be willing to pay the extra price for equipment
16 that will minimize contamination of water supplies?

17 The research and development activities within the state universities and the federal
18 government are directed toward both, the small farmer and the larger farmer, as well as the
19 commercial chemical applicator. Many of the small farmers depend on the custom commercial
20 applicator for application of agrichemicals. These small farmers do not want to invest resources
21 and time into agrichemical application activities. Many of the problems being addressed by the
22 public research agencies apply to both the small and large farmer. In the case of the large farmer,
23 they might own the equipment, while the small farmer may use a custom applicator. Technology
24 to increase the efficiency of agrichemical application is the same whether this technology is used

1 on a small tractor-driven low-pressure sprayer or a large self-propelled sprayer used by a large
2 farmer or a custom applicator.

3 There are some alternatives to farmers owning their own a highly specialized,
4 relatively expensive applicator. The custom applicator enterprises would have to increase
5 significantly. The support of those custom enterprises would ultimately cost the farmer, but not as
6 much as if they all were required to purchase this new technology. It seems that the concept of
7 either custom applicators or cooperative purchases may be hard to implement in the Mid-West
8 where farmers are simply not used to farming that way. However, wheat farmers in West are used
9 to having all their grain harvested by custom harvesting enterprises. It may be possible for farmers
10 to adapt to using more custom application of agrichemicals. Many of the chemical and seed
11 dealerships or also owned by farmers. It would be feasible for some farmers to enter into the
12 custom applicator business as another outside enterprise like they now are doing with seed,
13 fertilizer, and some pesticides.

14 III. Congressional policy options

15 The policy issues for improving agrichemical application equipment have been addressed
16 in several recent reports (10,11,12). These policy issues are summarized as follows:

- 17 ■ Recognize research priorities established by the Agricultural Research Institute sponsored
18 conferences of 1985 and 1988.
- 19 ■ Encourage public research agencies in the proprietary development of equipment and
20 non-specific chemical formulations.

1 ■ Support centers of excellence that have multiple discipline research directed to solving
2 agrichemical application equipment problems.

3 ■ Establish fellowships and grants for cooperative government/industry partnerships in
4 proprietary development of agrichemical application technology.

5 ■ Support cooperative standards organizations that develop standard engineering practices
6 and procedures for storage, mixing, and transfer of agrichemicals.

7 ■ Increase support for applicator training programs so these programs reach all operators
8 of application equipment.

9 ■ Encourage the development of a center for aerial application research that would improve
10 aircraft and aerial equipment used for applying agrichemicals.

11 ■ Establish an assessment program to determine the extent and accuracy of present-day
12 technology for applying agrichemicals.

13 The priorities for research required to provide the knowledge for solving the problems
14 associated with the application of agrichemicals have been well documented in recent reports and
15 publications (10,11,12). Some of these that are of particular interest from the standpoint of water
16 quality are:

1 1. Develop closed pesticide delivery systems for ground and aircraft sprayers.
2 These sprayers would meter and inject concentrated pesticides from returnable,
3 reusable containers into a diluent supply line, thus eliminating premixing of sprays.
4 These systems along with on-site activated carbon filtration systems would virtually
5 eliminate point source contamination of water sources.

6 2. Develop methods to increase pesticide deposition efficiency on plant foliage.

7 3. Develop prediction models and expert system computer techniques for decision
8 support systems to manage agrichemical application.

9 4. Improve agrichemical application equipment control systems by developing sensors
10 for measuring variables in the field that affect the use of agrichemicals.

11 5. Develop improved facilities, equipment and procedures for the handling,
12 packaging, and transfer of pesticides.

13 The development of improved agrichemical application equipment will depend on the
14 cooperative effort of public research agencies and private enterprise. Scientists and engineers at
15 universities and within federal research agencies should be encouraged to enter into the joint
16 development of equipment for applying agrichemicals. This type of joint venture is very important
17 since the research capabilities of the industry are almost non-existent and the ability to do the
18 development work is almost foreign to most scientists. Neither the time or resources are available
19 to do the research and development independently. Many of the machinery manufacturers have
20 excellent capabilities to do development research, but lack the ability to do the fundamental

1 research needed to furnish knowledge for the developer. Some type of incentive should be available
2 to encourage such joint ventures.

3 There are already some excellent centers where agrichemical application equipment research
4 is underway. These centers should be expanded with latest equipment and scientific expertise to
5 properly address the problems. The centers already have working relationships with the farm
6 equipment industry and could form the nucleus for an expanded research program.

7 There is an urgent need to establish consensus standards for the agrichemical application
8 industry. Such standards are rather routine for the handling of chemicals in other industries.
9 Many of these industrial standards require modification for both on-farm and commercial applicator
10 use. Funds are needed to encourage the rapid development of these standards and procedures,
11 especially for storage, mixing, and transfer facilities.

12
13 The applicator certification program should be evaluated and modified to reflect changes
14 in the concern for protecting water supplies. Most of the programs now require that at least
15 someone that is in-charge be subjected to the training. New training programs should be aimed
16 at all users of pesticide application equipment and not just to the one or two people than may be
17 responsible for the use of application equipment.

18 There is a need to determine the extent that improper application of agrichemicals is
19 affecting water quality. The amount of acres applied with certain types of sprayers is not known
20 under present-day farming practices. Survey data is available for the 1960's when such farm
21 programs as the CRP where not in existence. These programs and the general economic climate
22 in rural America has change significantly since those surveys were taken. These data bases need
23 to be updated.

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